EVALUATION OF PORE-SIZE DISTRIBUTION OF POROUS MEDIA FROM CAPILLARY PRESSURE CURVES— A NETWORK APPROACH

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CERTIFICATE

It is certified that this work has been carried out under my supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

Porous media are interconnected networks of void space of multitude shapes and sizes. Attempts in developing an analytical expression for the fluid flow behaviour through them have not been satisfactory to-date. The classical model of the bundle of tubes is too simplified a model to be realistic and useful. In the present work the flow behaviour of porous media has been modelled by a network of interconnected tubes of different sizes. An attempt has been made to extend the concept of relating pore-size distribution (both volumetric and number) to the capillary character of the network. The validity of 'ink-bottle' effect has been tested by the comparison of capillary pressure data with the actual tube size distribution of the network.

The extent of inter connection between the pores in a network is found to be a very important factor influencing the shape of the P_c curves. Therefore, any model of porous media based on bundle of tubes concept is likely to give erroneous results. Fatt's model, however, may be used with modified value of the exponent (between -2.5 to -3.5) to give better result for the number distribution. Similarly while correcting the measured pore-size distribution (volumetric) by Meyer's method, it has been found that the relation $V \propto r^{1.5}$ improves the interpretation. These values for exponents have been obtained

for networks with six tubes (on the average) meeting at a node point. The modified values of exponents perhaps correct for inter_connection between the pores.

CHAPTER 1

INTRODUCTION

Porous media, whether in the form of natural rocks or particulate aggregates such as powder-packs, have quite a few interesting properties compared to the properties of their bulk solid phase. One such property, the flow of fluids through them, has been engaging the attention of scientists in many disciplines. The petroleum engineers are interested in knowing the quantity and the maximum possible rate of fluid withdrawal from reservoir rocks. The soil-scientists concern themselves with the distribution and movement of soil-moisture. Chemical engineers, likewise, dealing with the problem of drying, are faced with the question of determining the rate at which the moisture from the pores can move up to the surface. Similarly while analyzing the performance of a packed bed, it is pertinent to evaluate the effectiveness of mass-transfer as well as liquid hold-up. Internal void structure is important in determining the effectiveness of batteries as well as the moisture movement capacity of the concrete and bricks.

The total internal surface area, porosity or permeability do not provide adequate information about the complex pore structure of porous media. Quite often, it is necessary not only to know these cumulative properties but also the distribution of pore sizes. The shapes of the relative permeability

and capillary pressure curves are markedly affected by pore-size distribution. Of the two, relative permeability does not seem to be suitable for determining the pore-size distribution because of the averaging effect associated with the flow phenomena in the whole spectrum of pore-sizes. Capillary pressure, on the other hand, is a unique function of pore-size, interfacial tension and wettability. Keeping the latter two quantities constant it is possible to estimate the sizes and proportions of the contributing pores from the successive higher values of capillary pressure.

Capillary phenomena comes into play whenever a fluid/fluid interface is in contact with a solid surface. Due to unequal interfacial tensions, fluid adjusts itself to attain thermodynamic equilibrium, thereby minimizing surface free energy. The well known Laplace equation which relates the various quantities affecting capillary pressure is

$$P_c = \gamma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \qquad (1.1)$$

where P_c = Capillary pressure,

γ = Interfacial tension

r_1 & r_2 = Two principal radii of curvature of the surface at any point.

The implicit assumption that the sum of reciprocals of the two principal radii of curvature (mean curvature) is the same at every point on the equilibrium surface, is a

mathematical consequence of the fact that the surface area tends to a minimum (i.e. spherical or nearly so in most cases). All methods of pore-size determination, that make use of capillary pressure are based on the hypothesis that the mean curvature of an equilibrium liquid surface can somehow be related to the pore-size. This relationship is difficult to establish for any shapes other than that with the simplest geometry. For straight cylindrical capillaries, Laplace's equation can be written as

$$P_c = \frac{2\gamma \cos\theta}{r} \qquad (1.2)$$

where θ is the angle of contact of the interface through the wetting phase and r is the radius of the capillary. This equation can correctly predict the pore-sizes and their distribution if bundle of parallel tubes is a valid model for porous media. For real system, this is an obvious over simplification and the equation will relate the capillary pressure to the radius of the largest opening leading to the pore rather than the radius of the pore itself. But in the absence of a better known method this pore entry radius is taken as a measure of the actual pore-size. Implied in this is the assumption that the actual pore-size is some unique function of the pore entry size for pores of all sizes. This however is difficult to justify.

In capillary pressure experiment with porous media, the sample is gradually desaturated of the wetting phase by

injecting some non-wetting fluid (making known contact angle with the solid surface) at successive higher pressure. At equilibrium, the capillary pressure opposing the entry of non-wetting phase, P_c; is balanced by the externally applied pressure. This P_c when put in Eq.(1.2) gives the radius of the smallest pore, r, invaded by the non-wetting phase. Knowing the saturation of the non-wetting phase in the sample at the stage, we arrive at the value of the fractional pore volume contained in the pores with radius greater than or equal to r. By successively increasing P_c, non-wetting phase is forced into smaller and smaller pores and the fractional pore volume corresponding to different values of r can be obtained. This method has been universally used for the calculation of volumetric pore-size distribution in porous media.

For fluid flow calculations, the pore number distribution is the desired quantity. To arrive at the number distribution from volume distribution, it is essential that we make some assumption about the pore-geometry and its dimensions. For parallel tube model of porous media, the quantity in question is the relation between the tube radius and length. Based on the assumption that $l = Cr^{\alpha}$, where C is proportionality constant and r is radius, Fatt[1] derives the number distribution function as follows:

$$f(r_2-r_1) = \frac{\int_{S_1}^{S_2} P_c^{2+\alpha}\, ds}{\int_0^1 P_c^{2+\alpha}\, ds} \qquad (1.3)$$

where $f(r_2-r_1)$ = frequency of occurrence of pores in the interval r_2-r_1

S = saturation of the non-wetting phase

There is considerable disagreement between different workers in the field about the value that α should assume. Whereas Fatt[1] proposes a value of -1. Meyer[2] implicitly takes this as 1. Dallavalle[3] seems to have some experimental results to back his suggestion of the value between 0 and 1. In the absence of a conclusive evidence, this factor still remains uncertain.

The method just discussed is essentially empirical in nature. For quantitative description of flow phenomena in porous media, a functional relation between the pore-size distribution and capillary pressure curve is needed. It will be our endeavour in the present work to examine the existing models and suggest one which can reasonably interpret the experimental P_c vs saturation curves in terms of pore-size distribution.

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CHAPTER 2

LITERATURE REVIEW AND ANALYSIS

Natural porous systems can be viewed as inter-connected network of voids of different shapes and sizes separated by interconnecting links or necks. Often the behaviour of such a system is approximated by a bundle of capillaries[4]. Dullien and Batra[5] have collected a comprehensive list of references of the attempts made in this direction in their review article. It is apparent that very few real porous media will contain pores of the straight cylindrical shapes, and therefore the pore radii calculated from the capillary pressure have to be considered as equivalent pore radii. This is defined as the radius of a straight cylindrical capillary that would give rise to the same capillary pressure as the measured value. Since a variety of different capillary shapes may give rise to the same capillary pressure, the pore dimensions calculated from capillary pressure measurements are at best semi-quantitative. The equation relating properties of porous media to the radius distribution of the equivalent bundle of tubes have been given by a number of authors[6-9]. However, apart from the mathematical simplicity associated, the most glaring weakness of the model is the prediction of highly anisotropic properties. Porous systems on the other hand are known to be isotropic in nature. Inspite of its success in correlating certain properties viz. permeability

formation factor etc., the model has failed to approximate the capillary pressure vs saturation and its hysteresis.

For more complex systems, such as random packing of non-spherical particles, Carman[4] suggests that twice the hydraulic radius is the suitable value of r in the following expression for P_c:

$$P_c = \frac{2\gamma \cos\theta}{r} \tag{2.1}$$

where the hydraulic radius is defined as the ratio of porosity f to the surface area A in unit bulk volume. A more accurate account of the curvature for different geometry of the capillary is given by Gregg and Sing[10]. On substitution Eq.(2.1) is reduced to

$$P_c = \frac{\gamma \cos\theta \, A}{f} \tag{2.2}$$

Substituting the expression for the specific surface area in terms of permeability K and porosity, from the Kozeny[11] equation, Eq.(2.2) becomes

$$\frac{P_T}{\gamma}\left(\frac{K}{f}\right)^{\frac{1}{2}} = \left(\frac{1}{k}\right)^{\frac{1}{2}} \tag{2.3}$$

where the threshold pressure P_T has been substituted for P_c. k is an empirical textural constant of the medium and accounts for the deviation of a porous system from the model.

This was obviously a gross simplification, and Carman himself points out that, for porous bodies with widely varying pore-size distribution, calculations based on Kozeny-Carman

model can be quite wrong.

Sphere Pack Model:

The earliest attempt in approximating the flow behaviour of porous media was their simulation by packs of uniform spheres. But the complexity of the pore-geometry in sphere-packs prevented the derivation of an accurate and meaningful description of flow behaviour through them. Recognizing the difficulty, Kozeny[11] inductively developed an equation relating permeability to porosity and internal surface area of a sphere-pack.

$$K = \frac{C\ f^3}{TS^2} \qquad (2.4)$$

where f = porosity

T = tortuosity

S = specific surface area

Kozeny equation, as modified by Carman[12] and given as

$$K = \frac{f^3}{k\ S^2(1-f)^2} \qquad (2.5)$$

did not prove to be of much value, aside from its use in estimation of the surface area of powders.

A comprehensive review of the use of sphere-packs to model the flow behaviour of packed beds, has been given by Haughey and Beveridge[13]. In their analysis, the emphasis has been in arriving at the mean fractional voidage for both regular and random packing, on the basis of the position coordinates and the coordination numbers, rather than the pore -

geometry. Generally speaking, particle shape and size distribution are the two factors most likely to affect the packing structure and its properties. Some work has been carried out on the densest packing of non-spherical particles. But the multiplicity of packing types with the same coordination number and vice versa, accompanied by the size distribution of particles further complicate the pore structure. Hence the task of analytical description is rendered almost hopeless.

The problem of capillary hysteresis in uniform sphere packs was studied by Kruyer[14], Frevel and Kressley[15], Meyer and Stowe[16,17] and more recently, by Melrose[18]. Their analysis points out that the curvature of the invading interface of non-wetting phase is generally larger resulting in higher value of capillary pressure compared to the retracting interface associated with imbibition. This, according to them, may be the reason for the porous media exhibiting capillary hysteresis.

Naar and Wygal[19] view any porous media as a random mixture of spherical particles and propose a model based on the principle of averaging the properties of the basic sets to arrive at the mixture-properties. The problem essentially is finding of appropriate weighting factors to average the basic set properties, determined experimentally. Expressions for porosity,permeability and capillary pressure behaviour of the porous media have been developed. But the experimental support to this model is too meagre to be accepted.

Network Model:

The description of single and multiphase fluid flow through capillary pores in porous media has been unsatisfactory because the pore-geometry is too complex to be described adequately by analytical expression. Markin[20] used a model consisting of a system of randomly arranged intersecting voids with circular cross-section and continuously varying radius. No more than three branches could converge at any point in the net_work. This model, however, does not seem to have gained the favour of the research workers in the field.

Fatt[1] replaced each pore with a cylinder in his two dimensional network with different grid patterns. He could incorporate random assignment of parameters, such as pore-size distribution and number of cylinders meeting at a node point, in the model. Fluid flow in the network could be followed as one pore after another was desaturated.

All of Fatt's calculations were performed assuming a continuous wetting phase in the tubes. As a consequence, no wetting phase could be trapped in a desaturation process. Dodd and Kiel[21] extended this work by applying desaturation steps such that wetting fluid could be trapped. Cylindrical pores were assumed to contain only one fluid at a time; thus allowing the displaced fluid to be trapped if no continuous path to the effluent end was available. Thus at any time the pore could be either full of wetting phase or non-wetting phase.

Singhal[22] modified Fatt's model by providing for the possibilities of different flow regimes in different channels during desaturation process. The four basic flow regimes viz. single phase flow, displacement, annular and slug flow were allowed to occur any where in the model whenever suitable conditions existed. In addition, he substituted triangular capillaries for circular shaped tubes to account for funicular flow regime over extended range of saturation. A trapping factor, evaluated from the comparison of the model with the experimental results, was used to effect trapping of fluid. This model has duplicated the relative permeability behaviour of porous media reasonably well and we propose to use the same model for approximating its capillary pressure vs. saturation behaviour.

Other Model:

Haring and Greenkorn[23] have proposed a parametric statistical model, from the theoretical considerations, to calculate the macroscopic properties such as saturation, permeability and dispersion coefficient in porous media. Porous medium is approximated by a large number of randomly oriented straight, cylindrical pores with randomly varying radius and length. The relationship between saturation and P_c contains two constants which are the parameters of the pore-size distribution function. They maintain that the two parameter incomplete Beta function can adequately represent

most of the pore-size distributions encountered in porous media. Non-uniformity of a medium can be incorporated by adjusting the magnitude of the two parameters in the distribution function. Of all the models proposed to-date this appears to be the most promising for analytical description of flow phenomena as well as mass transfer through porous media.

Paytakes[24] et al, while developing a model for the packed bed, point out some in-consistency in Haring and Greenkorn's model. Whereas in Haring's model the minimum tube size is implicitly assumed as zero, the smallest pore-size in a packed bed is definitely not zero. As a consequence, the average pore diameter calculated from this model are smaller than the smallest pore calculated from sphere pack model. The calculated pore length is about equal to the half the average grain diameter of the pack. However, this minor inconsistency in the model can be removed by substituting for the finite value of the smallest pore-size for packed bed and thereby slightly modifying the model.

In their own model, Paytakes et al assume convergent-divergent circular tubes as the basic units of which a packed bed is assumed to comprise of. These basic units do not have any lateral connection thus allowing fluid flow only in the vertical direction. By introducing convergent-divergent flow channels, they seem to have accounted for inertia effects in

flow path. However, this could not be a realistic approach for porous media where interconnections are quite important in considering the flow behaviour.

2.2 Pore-Size Distribution:

It is obvious that pore-size distribution is very important in describing fluid-flow through porous media. Ritter and Drake[25] proposed a method of determining the pore-size distribution from mercury porosimetry data. The basis of this method is the concept that mercury is forced into gradually smaller pores against capillary forces as the pressure is increased. The fact, that such information does not directly give the pore-size distribution is obvious. However, pore-size distribution obtained from Nitrogen adsorption agrees well with that calculated from mercury porosimeter data on the assumption of parallel tube model.[26] Mercury porosimetry will not detect the dimensions of those pores that are accessible only through necks narrower than the pore itself. The volume of these pores of limited accessibility will be erroneously assigned the dimensions of the largest neck leading to these pores. They analyzed a number of natural substances and concluded that the pore size distribution can be represented by three parameter modified Maxwellian distribution function. Haring's two parameter distribution function is simpler and should be preferred.

Meyer[2] attempted to correct this distortion in the pore-size distribution due to the presence of the pores of limited accessibility. On the assumption that the pore sizes follow Poisson distribution, he calculated the probability of a pore of radius r_o not being connected to the pores of radius $r \geqslant r_o$. This probability was used to correct the mercury porosimeter values for the 'Ink-bottle' effect. The details of the derivation and the computational method is given in Appendix B.

Dullien[27] proposed to determine 'two dimensional' pore-size distribution by injecting Wood's metal into the sample and using micrographic analysis. Apart from the experimental scheme, he has not published his results yet.

2.3 Characterization of Porous Media on the Basis of Capillary Pressure Curve:

The earliest attempt in this direction was made by Leverett[28,29] who put forward a semi-empirical relation

$$J(S_w) = \frac{P_c}{\gamma \cos \theta} \left(\frac{K}{f}\right)^{\frac{1}{2}} \qquad (2.6)$$

where $J(S_w)$ = capillary pressure function and is dimensionless function of wetting phase saturation

on the basis of dimensional analysis. Leverett's data showed that a plot of $J(S_w)$ vs S_w (wetting phase saturation) yielded a unique curve which described the capillary retention of wetting liquid in clean, unconsolidated sand.

Rose and Bruce[30] extended Kozeny-Carman treatment to relate capillary pressure with porosity, permeability and textural constant known as Kozeny constant. The expression suggested is:

$$\frac{P_T}{\gamma \cos\theta}\left(\frac{K}{f}\right)^{\frac{1}{2}} = \left(\frac{1}{k}\right)^{\frac{1}{2}} \qquad (2.7)$$

where P_T = threshold pressure i.e. $\lim_{S_w \to 1} P_c = P_T$

But these expressions, apart from classifying the porous media and in some cases predicting flow behaviour, did not give any insight in the distribution of the pore-sizes. Recently Haring and Greenkorn[23] have derived an expression for wetting phase saturation from P_c curve as

$$S_w = \frac{\int_0^{\frac{1}{P_c^*}} \left(\frac{1}{P_c^*}\right)^{\alpha+2} \left(1 - \frac{1}{P_c^*}\right)^{\beta} d\left(\frac{1}{P_c^*}\right)}{\int_0^{1} \left(\frac{1}{P_c^*}\right)^{\alpha+2} \left(1 - \frac{1}{P_c^*}\right)^{\beta} d\left(\frac{1}{P_c^*}\right)} \qquad (2.8)$$

where $P_c^* = \frac{P_c}{P_T}$

P_T = threshold capillary pressure

α & β = parameters of pore size distribution.

Thus in case we are able to estimate α and β from P_c vs S_w curve, we really have an expression for pore-size distribution F(x),

$$F(x^*) = \frac{\int_0^{x^*} x^{\alpha} (1-x)^{\beta}\, dx}{\int_0^{1} x^{\alpha} (1-x)^{\beta}\, dx} \qquad (2.9)$$

where $x^* = r/r_{max}$, the ratio of pore-size to the largest pore size.

This $F(x)$ is then used to calculate the wetting fluid saturation, S_w, for any P_c by the Eq. (2.8).

2.4 Plan of Attack:

From the analysis of the past work, it is obvious that the relation between the pore-structure, its distribution and the capillary characteristics of porous media is not well understood. Meyer[2] assumed Poisson distribution and suggested a method for applying correction for 'ink-bottle' effect. Haring and Greenkorn[23] suggested a statistical model for capillary pressure which could be useful in mass transfer calculations. But they approximated the pores by straight cylindrical tubes beside assuming unimodal distribution of the pores. In real porous media these are not strictly valid assumptions. In the interpretation of P_c curve for pore-size distribution, Fatt[1] used an arbitrary factor (α) which could take the value -1. There seems to be considerable disagreement between different workers regarding the value of this factor, α. Meyer[2] had implicitly assumed the value 1 for α in his calculation of

of probability function for the pores of limited accessibility.

To find a method which can interpret P_c curves satisfactorily, we will do the following:

a) Networks will be constructed for different pore-size distributions and by allowing them to imbibe nonwetting fluid under successively higher pressure, P_c curves will be generated for different distributions.

b) An attempt will be made to workout a procedure for interpreting P_c in terms of the pore-size distribution. To arrive at the number distribution of the pore-sizes from P_c curve, Fatt's[1] model with different values of α will be tried and the result willbe compared with the actual input to the network.

c) Existence of 'ink-bottle' effect in a real porous system will be studied by the method proposed by Meyer[2]. The corrected pore-size distribution (volumetric) will be matched with the one estimated from the P_c curve to determine whether the effect is significant in natural system. Corrected pore-size distribution from the network P_c curve will be compared with the actual distribution to test the reliability of the approach. To this end, different expressions for characteristic volume, in Meyer's method, in terms of power to pore radius, will be tried and compared with the actual input to the network.

d) To obtain the pore-size distribution from an actual P_c curve, Haring and Greenkorn[23] model will be used to estimate

the parameters of distribution by non-linear least square method. Network model will be used to determine how close the estimated distribution is to the actual distribution.

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CHAPTER 3

MODELS USED IN THE PRESENT WORK

3.1 Generation of P_c Curve from Known Pore-Size Distribution:

Use of network model for generation of P_c curve consists of two steps:

a) Construction of a network simulating the porous material with a known pore-size distribution. This idea was originally suggested by Fatt[1] and the methodology followed here was developed by Singhal[22]. In the network, pores could merge at and branchout from a node point. A network of the size 6 x 8 was used in our simulation in which the nodes were arranged in square grid pattern. Thus at each node point a maximum of eight tubes could meet. Fatt[31] suggested, from experimental observations that each tube was connected to 10 other tubes implying that on the average 6 tubes could meet at a point. This fact was incorporated in the model by modifying the cumulative pore-size distribution obtained from capillary pressure curves, so that 25% of the tubes have zero radius. This was achieved by compressing the real distribution between 0.25 to 1.0 instead of 0.0 to 1.0 by the following expression:

$$l' = 0.75l + 0.25$$

where l' = new value of the distribution

l = original value

Whereas the tube radius and location were assigned in random manner by Monte-Carlo technique, the tube length could assume only two values viz. equal to the side length of the square or its diagonal length. The grid length was arbitrarily chosen. The list of the input to a typical network simulation program is given in the Table 1. The details of simulation has been discussed by Singhal[22] and for the sake of completion, the relevant points are included in the Appendix A.

b) Generation of Capillary Pressure Curve: Capillary pressure characteristics of the network is evaluated by modifying and adapting the computer program written by Singhal[22]. Some additional checks have been introduced in the program to verify that material balance for each fluid as well as for the total fluid is satisfied at each stage of computational cycle.

Initially the network is assumed to be full of wetting fluid and is allowed to be displaced by non-wetting fluid. A fixed pressure drop (ΔP) is applied across the network and it is allowed to desaturate the wetting fluid in a quasi-static manner. This process continues till outflow from the network in a particular time step is negligibly small; implying equilibrium fluid distribution in the model. Theoretically in a quasi-static process the time step should be as small as possible. But this would mean larger computation time. Hence we used the time steps of the order of 200 μsec. initially and later increased it as the desaturation process proceeded.

Instead of waiting indefinitely for zero outflow to occur in a time interval, we cut short the calculation for a ΔP whenever the outflow in a time step is less than or equal to 1% of the outflow in the first time step. The saturation of the wetting phase in the model is then calculated thus obtaining one point on the P_c vs S_w curve. Pressure drop (ΔP) across the model is then successively increased and in each case the equilibrium wetting phase saturation is obtained. In this way the whole P_c vs S_w curve can be obtained over any range of pressure and saturation.

Singhal[22] used a trapping factor $(0.2/\sqrt{\mu_o \mu_w})$, where μ_o and μ_w are the viscosities of non-wetting and wetting fluid respectively, to trap the fluids in the pores during desaturation. This was merely a correction factor to match the model behaviour with actual samples. In static process like capillary desaturation, the viscosity of the fluid is not of any significance as far as equilibrium saturation is concerned. Equilibrium saturation of the wetting fluid depends solely on the curvature of the remaining fluid interfaces in various tubes. In our simulation of the network the tubes have assumed the size equivalent to the volumetric average radius of the pores. In real porous systems (granular) the pores are convergent-divergent in shape. As a result the neck radius in any tube is definitely smaller than the volumetric average radius. As the capillary pressure of any tube is determined

by the size of the narrowest constriction in the tube, the actual capillary pressure will always be larger than that calculated from the average radius.

In the present work, the trapping factor is the ratio of the volumetric average pore radius to the neck radius for each tube, thus implicitly simulating the convergent - divergent shape of the pore channels. At every stage the pore-entry capillary pressure is modified by this factor to calculate P_T at the neck. This pressure is then used to determine whether the interface will move through the pore or will be blocked.

3.2 Correction for "Ink-Bottle" Effect:

In natural porous systems pores are surrounded by smaller pores; recognized as "ink-bottle" effect by Meyer[2]. This results in assigning larger volume to the smaller pores while the volumetric share of larger pores is less than the actual volume. Evidently the use of bundle of tubes model to calculate pore size distribution is likely to be erroneous. Meyer[2] attempted to correct the measured data for this effect by calculating the probability of a larger pore not being connected through equal or larger pores to the mercury source in mercury porosimetry. He assumed that pore-sizes are randomly distributed and follow Poisson's distribution. In deriving the probability $f_0\ (r_0, r)\ dr$, he overlooks the fact that the pores are mutually exclusive and asserts that this will not introduce any serious error in calculation since only

the 'zero' term in Poisson's distribution is used for calculation. Also, assumed randomness of pore sizes exclude from consideration clusters of very large or very small pores such as fractured or vuggy system.

Other simplifying assumptions made by Meyer are: (i) that the centre of an r pore lying in volume $v(r_o, r)$ will ensure its being connected to an r_o pore, (ii) that only those pores which are isolated from all equal or larger pores will fail to fill and (iii) volume of a pore may be expressed as Kr^3 where K is a constant.

The first assumption is valid for spherical pores and seems intuitively sound for others. The implication of the second assumption is that isolated groups of mutually connected pores are not being considered. This, of course, is a serious simplification but necessary for handling the difficult subject of aggregates in a random distribution. It is hoped that the correction applied for individual isolated pores is the major correction needed. The third assumptions implies that larger pores have larger length associated with them. This sounds reasonable as the larger pores are associated with larger grains for uniform packing. This assumption has one snag that K is not a constant. However, K as a constant appears only under the integral sign and cancels out. The assumption, in fact, is not that K is a constant but that its mean value in one integral is equal to that in the other.

Hence, he proposed that measured pore-size distribution should be corrected by this method to obtain actual distribution for granular porous system. Details of the method is given in Appendix B.

Computer program, written for this scheme, is given in Appendix D.

3.3 Haring and Greenkorn Model:

Haring and Greenkorn[23] have suggested the use of two parameter incomplete Beta function as the universal distribution function for the pore-size in a porous body. It was claimed by them, and rightly so, that almost any unimodal distribution, whether symmetric or skew, could be approximated very closely by the adjustment of the two parameters. Normal distribution of the pore-size was not favoured for the following two reasons:

i) the distribution is symmetrical.

ii) the independent variable varies from $-\infty$ to $+\infty$; none of which is strictly true for a porous media.

One more implicit assumption in their approximation is that the ratio of minimum to maximum pore size is zero, which is not always true. That seems to be the reason, why for a granular pack the average pore size computed on the basis of this distribution function comes to even less than the minimum pore-size computed from geometrical considerations of granular packing. Also, the average pore length is calculated to be equal to half the average particle diameter; while ideally

it should be equal. This fact has been pointed out by Paytakes, Tien and Turian[24]. However, this inconsistency may be over come by slightly modifying the distribution function to:

$$g(r^*) = \frac{\int_0^{r^*} (x-x_m)^{\alpha} \; (1-x)^{\beta} \; dx}{\int_0^1 (x-x_m)^{\alpha} \; (1-x)^{\beta} \; dx} \tag{3.1}$$

where r^* = dimensionless radius of the pore. The ratio of pore radius to the largest pore radius.

x_m = The ratio of smallest to the largest pore radii

α, β = Parameters of distribution.

Based on the assumption that the actual pore-size distribution can be approximated reasonably by incomplete Beta function, Haring[23] et al arrived at the following expressions for the wetting fluid saturation, S_w:

$$S_w = \int_0^{\frac{1}{P_c^*}} \frac{(\alpha+\beta+3)!}{(\alpha+2)!\,\beta!} \; x^{\alpha+2} \; (1-x)^{\beta} \; dx \tag{3.2}$$

$$= B\left(\frac{1}{P_c^*} ; \alpha+2, \beta\right) \tag{3.3}$$

where $B\left(\frac{1}{P_c^*} ; \alpha+2, \beta\right)$ is incomplete Beta function with $\alpha+2$ and β as parameters.

P_c^* Dimensionless capillary pressure, P_c/P_T

P_T Threshold capillary pressure i.e. P_c when $S_w \rightarrow 1$.

In this work we shall try to fit the Eq.(3.3) by non-linear least square method. Standard IBM program SDA-3094 will be used for this purpose.

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CHAPTER 4

RESULTS AND DISCUSSION

As already mentioned in earlier chapters network seems to be a good model for predicting the flow behaviour of porous media. A part from its closer and better physical similarity with porous media, capillary pressure curves obtained from it look quite realistic. However, there may be some weaknesses in this model which will be discussed later in this chapter.

Capillary pressure (P_c) vs wetting fluid saturation (S_w) from the networks are given in Figs. 2a to 2f. Each network was generated from a specified pore-size distribution, which was assumed to represent a hypothetical porous medium. Pore-size distribution used to generate networks were; arbitrary distribution, Beta distribution and Poisson distribution. Besides, a couple of bimodal arbitrary distributions were also used. The networks with bimodal distribution were used to find out if the P_c curve could give some indication of the multi-modality in the distribution. In each case, except the first network, the largest pore-size used was 20μ. The input distribution was compressed in each case between 0.25 to 1.0 to accommodate Fatt's Beta factor as suggested by Singhal[22].

Inspite of the very distinct and extreme forms of the distributions used to generate the networks, the calculated

P_c curves were not significantly different from each other. Thus giving the impression that capillary pressure is not a very strong function of the pore-size distribution in the network. Also threshold pressures (P_T) obtained from the network P_c curves (corresponding to $S_w = 1.0$) do not always agree with that predicted from the bundle of tubes model. Threshold pressure, from the definition, depends on the size of the largest tube in the input face of the network. But, in view of the fact that tubes are assigned randomly at different node points, it is possible that the largest size tube may not occur at the input face. In that case P_T predicted from the bundle of tubes model will be different from that evaluated from the network. From the inspection of Fig. 1.e, it is obvious that the largest tube size (20 μ) does not appear in the input face and hence the calculated P_T from the network is higher than that predicted for 20 μ tube radius (0.259 psi). Also, during the computation of P_c curve from networks, more than one fluid/fluid interfaces were observed in a continuous flow channel. This factor has not been accounted for in the bundle of tubes model and can be one of the reasons resulting in the difference in the two values of P_T.

Other features of the network likely to have influenced the P_c curves are; (i) number of tubes (ii) ratio of the tube length to the radius (iii) the extent of inter-connection between the tubesand (iv) existence of different flow regimes

in flow channels.

(i) Fatt[31] estimated number of pores in a 1/2" cube sample of sandstone to be of the order of 10,000. In our networks, the number of tubes varied between 89 to 101. Whether such a small number of tubes (pores) could reasonably approximate the flow behaviour of real porous media with huge number of pores, is open to doubt. With such a small number of tubes, it is the relative position of the tubes which matters more than the size distribution. If the investigation could be repeated with larger sizes of networks (500 to 1000 tubes), the result may throw some light over this question. Our limitation in computer memory and time prevented us from trying bigger networks. Fatt[1] asserts that tubes more than 200 in number do not substantially affect the nature of P_c curves from networks. However, he did not compare any experimental P_c curve with that of a network to prove his point that tube number is not a critical factor.

(ii) The second factor, which seems significant, is the ratio of the pore length to the pore radius. In our networks, this ratio varies from about 6 to 60 depending on the size and the location of the tubes relative to the grid. Earlier investigators suggest that the length of a pore varies according to some power of r. This factor varies between 0 and 1, according to Dallavalle[3]. Fatt[1] puts this value at -1. In one of our calculations grid size was reduced to about 1/5th

of the original value thus reducing the maximum value of length to the radius ratio from 60 to 12. The two P_c curves (Fig.1h) are not significantly different. Further investigation with different values of the grid-size is desirable before drawing any conclusion.

(iii) The third factor to be considered is the Beta factor suggested by Fatt[1] and used by Singhal[22] in his simulation of networks. This factor essentially represents the extent of interconnection between the pores in porous media. Applied to networks, this implies average number of tubes meeting at a node point. Fatt[32], from his experimental observations, points out that in a sandstone rock each pore is connected to 10 other pores thereby implying that on the average 6 tubes should meet at a node point. In Fig. 2h the three P_c curves have been obtained with different values of the Beta factor. It is obvious that the two P_c curves, for Beta factors 6 & 8, are not very different from each other, the P_c curve for Beta factor equal to 4 is significantly different from the other two. Hence it may be inferred that the extent of interconnection in a network, represented by Beta factor, is quite important and is likely to be different for different media. In our simulation this factor has been taken equal to 6.

(iv) There is experimental evidence to support the existence of different flow regimes in flow paths of physical models of porous media where one fluid displaces the other. In such systems, the interplay of viscous and capillary forces comes into existence and the flow regimes depend on ΔP and flow

rate. This phenomenon is accounted for in the network but not in the bundle of tubes model. This could be another weakness of the bundle of tubes model. However, for mercury-vacuum system this situation, of different flow regimes in flow paths, is not likely to occur.

Simulated networks used for generation of P_c curves were tested for goodness of fit by χ^2 test. The pore-size distributions of the simulated networks were not found to be similar to the input distributions within a reasonable confidence limit. We suspect that the scheme of pseudo random numbers used in the simulation might not have been truly random. Consequently it was decided to use the actual distributions of the networks rather than the input distributions which they were supposed to represent. Any further work in this direction should ensure that the simulated network does pass χ^2 test to represent the input distribution. However, the weaknesses mentioned above may not be very serious in view of the results obtained from the network model.

Since our networks have discrete pore-sizes, ideally some step type P_c curves would have been expected. But from the limited number of the points on the P_c vs S_w plot, a smooth curve could be drawn. It appears that the pore-sizes may not be the exclusive factor determining the value of capillary pressure in a porous medium. Other factors like connectivity etc might also be important.

The idea of relating P_c to the size of the pores has its root in the bundle of tubes model of porous media. Even the model proposed by Haring and Greenkorn[23] are the modification of the same model, providing random orientation of the tu tubes and consequent inter-connections. Therefore to correct for inter-connection between the pores, some modification is called for in the interpretation of P_c curves based on this model.

The effect of "ink-bottle" phenomena seems to be significant in the networks, resulting in the cumulative pore-size distribution (volumetric) obtained from P_c curves, being quite different form the actual distributions. Actual distributions were computed by counting the number of tubes of different size and calculating their volumes. The difference in the two distributions can be clearly seen in the Fig.3a to 3f. Attempts were made to correct the distributions (obtained from P_c curves) by Meyer's method[2] for "ink-bottle" effect. In using this method, slight modification was made in the scheme given in the Appendix B. As is obvious, in a network, tube lengths are independent of radius. As a result the pore volume as well as the characteristic volume defined in Meyer's method becomes proportional to the radius squared rather than radius cubed. The corrected distributions (volumetric) is compared with the actual and that obtained from P_c curves in Figs. 3a to 3f.

Effect of the pores of limited accessibility ("ink-bottle" effect) on the volumetric distribution appears quite-pronounced in some of the natural substances investigated by us. The substances included porous plate, fritted glass, pelleted gel etc. Meyer's method as given in the Appendix B was used for these calculations and the result is given in Fig. 4a to 4d. P_c data for these substances were obtained from Ritter and Drake[25] and are reproduced in the Table 3. The same method was applied to P_c data of some sandstone samples obtained from literature but no appreciable difference in the experimental and corrected distributions was observed; implying that this phenomenon is not very significant in those samples. In an attempt to closely approximate the actual pore-size distribution, the exponent of r in Meyer's method was given a number of values (3 to 1.5). The curves with the exponent equal to 1.5 were observed to be better than others in approximating the actual curves (Figs. 5a to 5f). Physically this means that the pore length is $\propto r^{-0.5}$. This distortion from the expected relation of $l \propto r^0$ may be due to a number of factors, like some bias in our networks, and to a greater degree on the extent of inter connection between the pores.

Attempts were also made to estimate number pore-size distribution from P_c vs S_w curves obtained from the networks. In the absence of an analytical expression incorporating network concept of porous media, investigations were carried out

to find out if Fatt's model, of bundle of tubes, could be useful. In that model (Eq. 1.3) Fatt[1] used an exponent α which related the pore length to the radius. The same equation, with the different values of α , was used to calculate pore-size distributions (number) from P_c curves of the networks. It is apparent from Figs. 5a to 5f that for the values of α lying between -2.5 to -3.5 (mostly -3.0) the calculated distributions are reasonably close to the actual distribution. The physical implication of this value is, that the pore length (l) $\propto$ $r^{-3.0}$. In our networks the tube lengths were independent of the radius. But because of the fact that we have distinctly two groups of lengths, side lengths and diagonals of the grid, in our networks, pore lengths could not be said entirely independent of the radius. Also, the small sample size, extent of interconnections and the non-randomness of the pseudo random numbers used in simulation, might have introduced some fictitious relation between l and r.

Haring and Greenkorn[23] model relating pore-size distribution (number) to capillary pressure and saturation, was tested by estimating the parameters of the distribution from P_c vs S_w curves by non-linear least square technique. These parameters were put back in incomplete Beta distribution function to calculate the number distribution. These calculated pore-size distributions did not match the actual distribution obtained by counting the number of the tubes from the networks.

One of the curves fitted to the network P_c curve is given in Fig. 6.

From the limited number of analysis performed by us, it is doubtful whether this model could at all relate the pore-size distributions to P_c curves of real porous media.

From our study it can be said that networks could be used as a valid model of porous media and pore-size distributions could be obtained from P_c vs S_w curves.

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CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

The classical model (bundle of tubes) of porous media have a number of weaknesses. As a result the interpretation of P_c curve based on this model is likely to be erroneous. Network is a better physical model of the porous media and P_c curves obtained from it is quite realistic. True pore-size distributions (volumetric and number) can be better estimated from P_c curves by modified Meyer's and modified Fatt's method indicated in this work.

Future work in this direction should ensure that the actual pore size distribution (number) of the simulated networks reasonably match the input distribution. More work is needed to find out the effect of tube length-radius ratio, the extent of interconnection, and number of tubes in the network on the P_c curve generated. Experimental work with physical networks are necessary to verify these theoretical findings.

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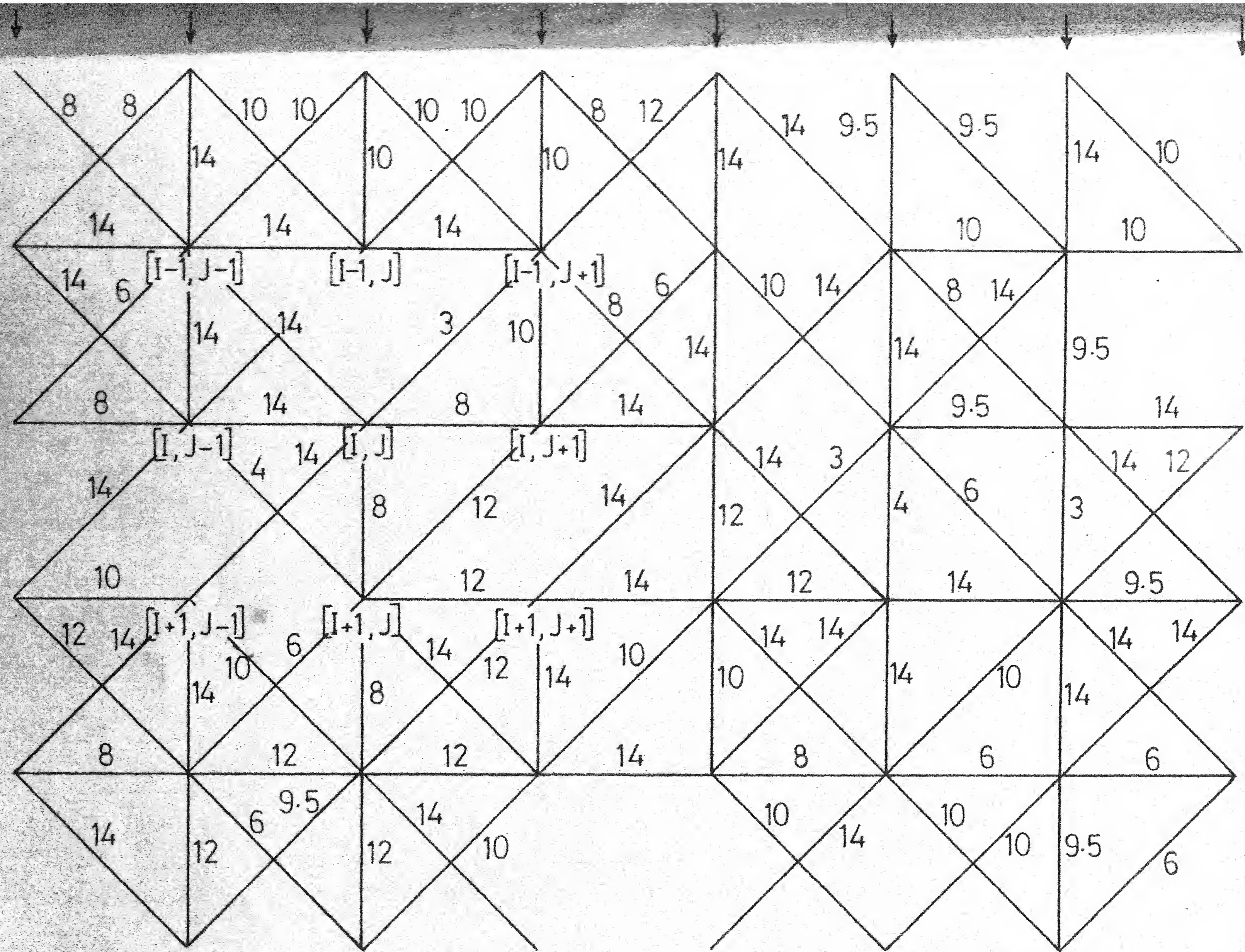

Fig. 1a - A typical network used for generation of capillary pressure curves. Input data table 1 . Numbers indicate tube rad. in microns.

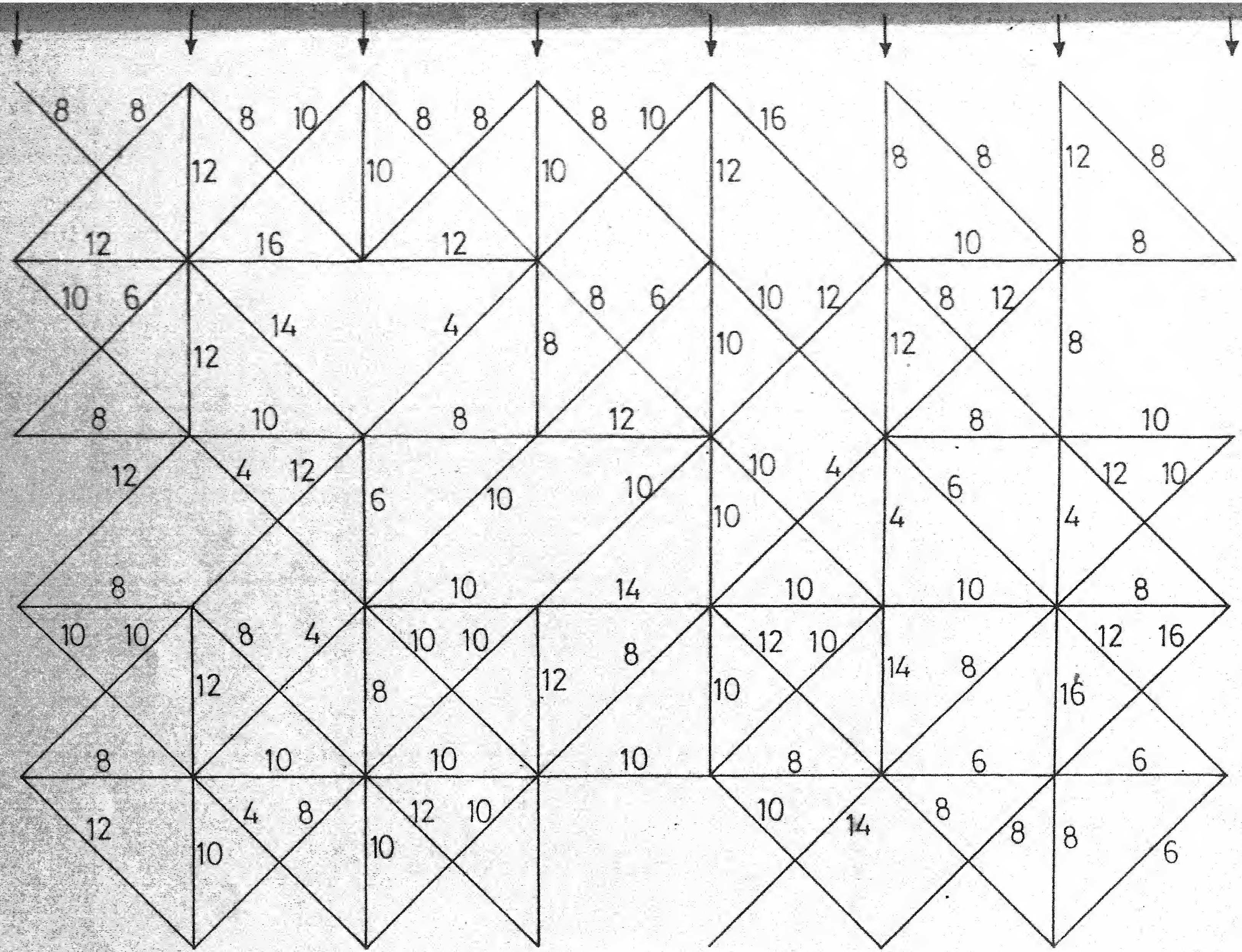

Fig.1 b- Network for incomplete beta distribution.
(Parameter 3·5,5·5)

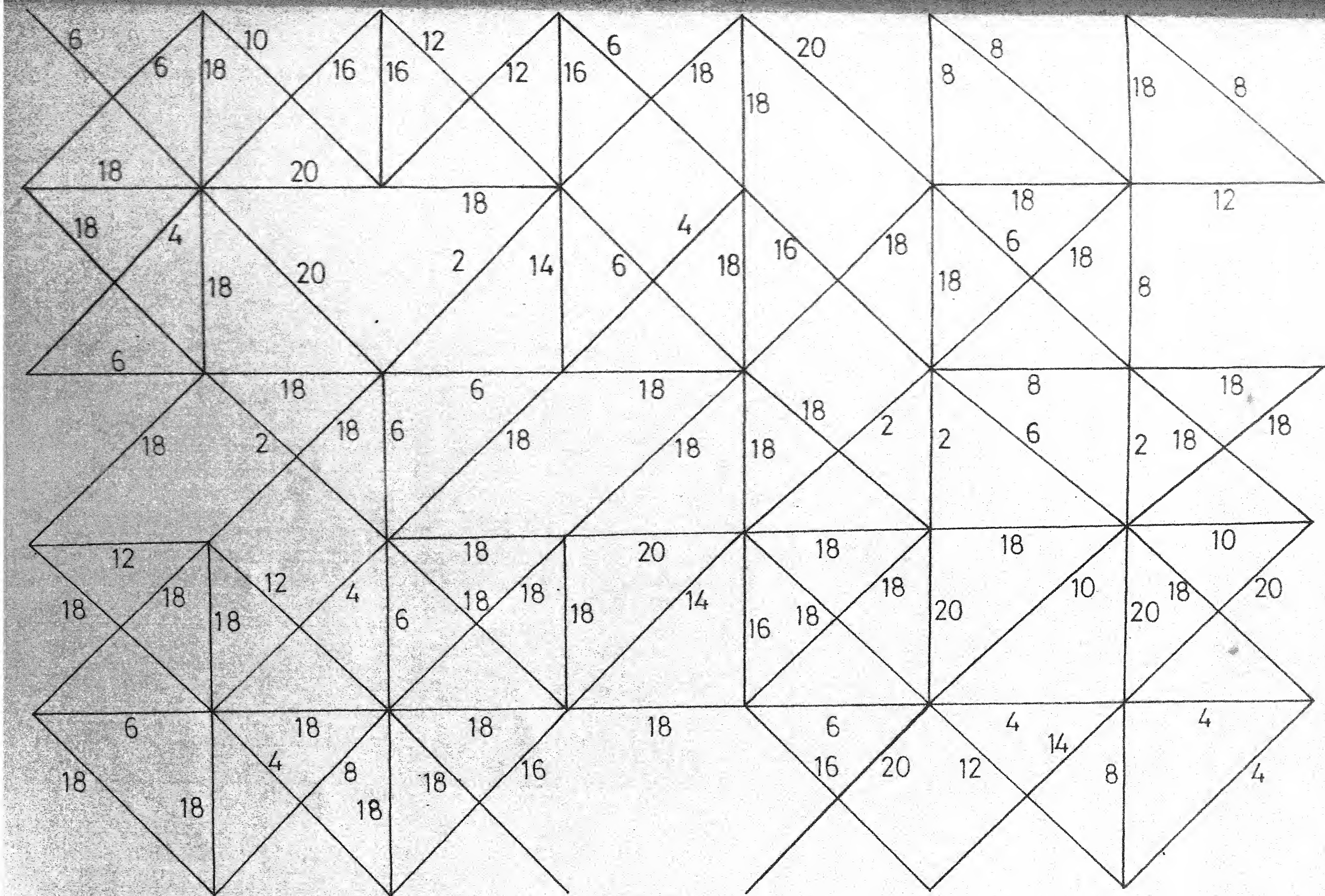

Fig. 1c – Network from arbitrary bimodal distribution. Table 2.

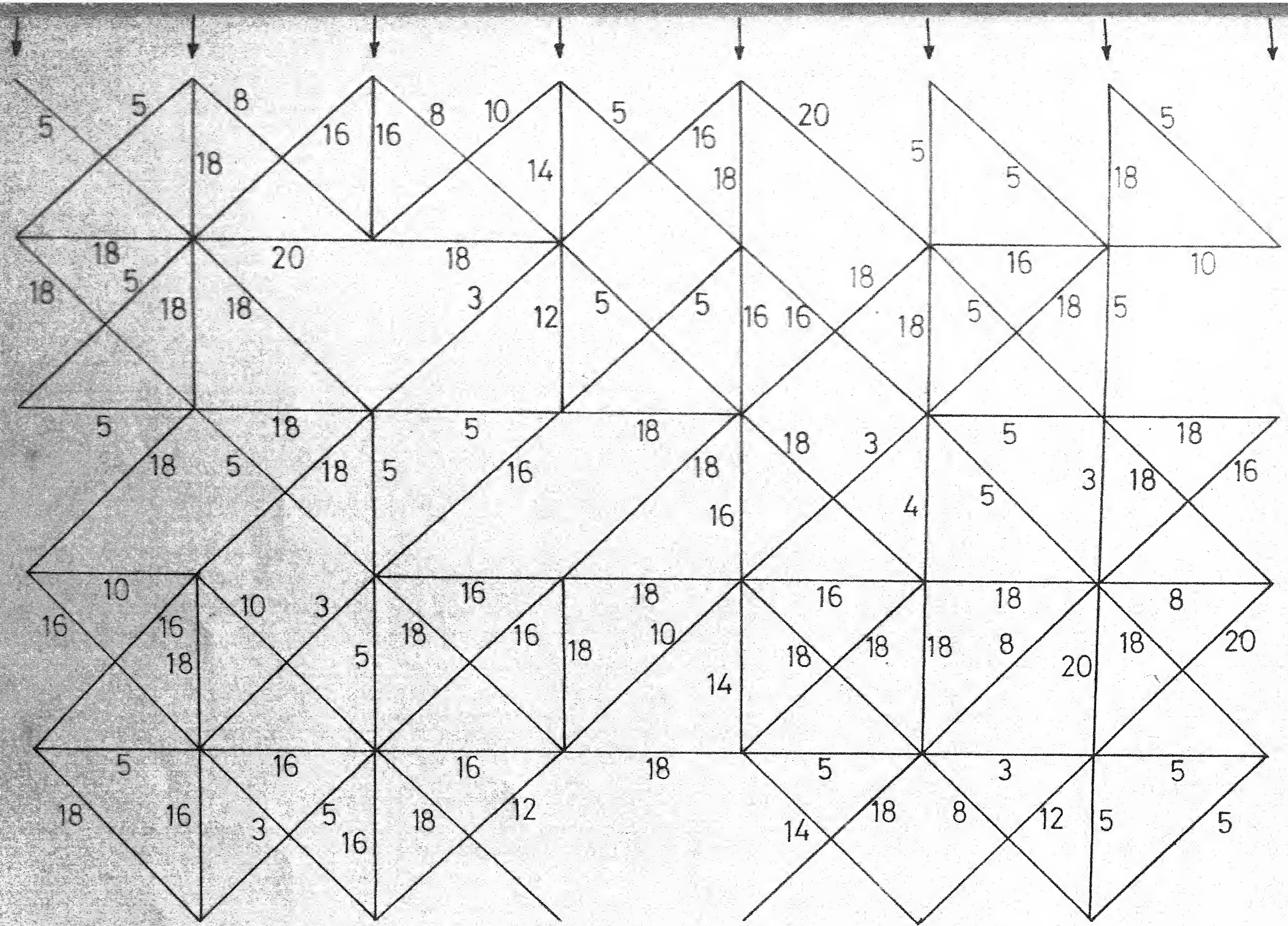

Fig 1 d - Network from arbitrary bimodal distribution. Table 2.

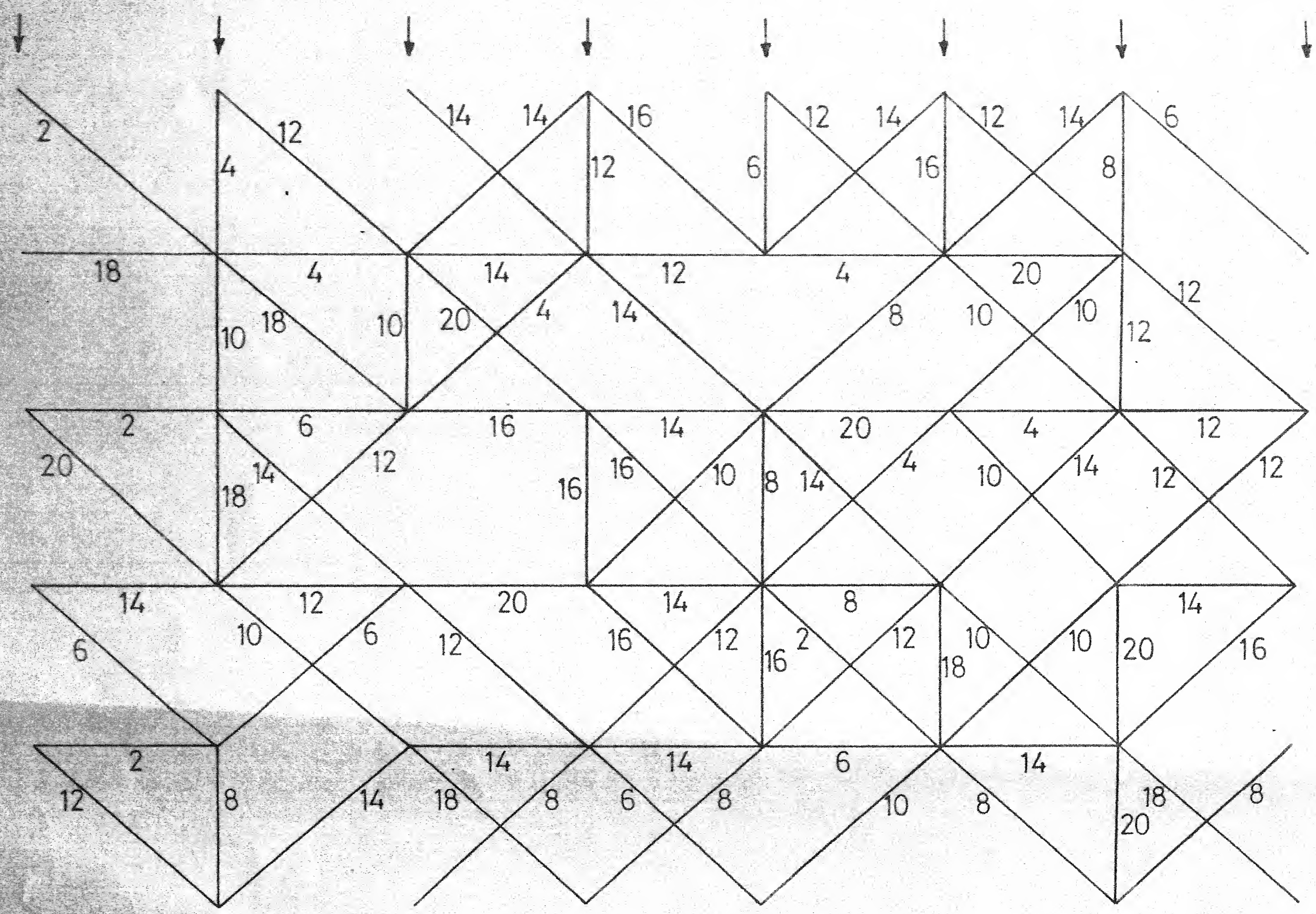

Fig.1e - Network used to obtain P_c vs. S_w curve (Fig.2e) indicating absense of the largest size tubes in the input end. Input incomplete beta distribution with parameters 1·0,1·0: Numbers indicate tube radius in micron.

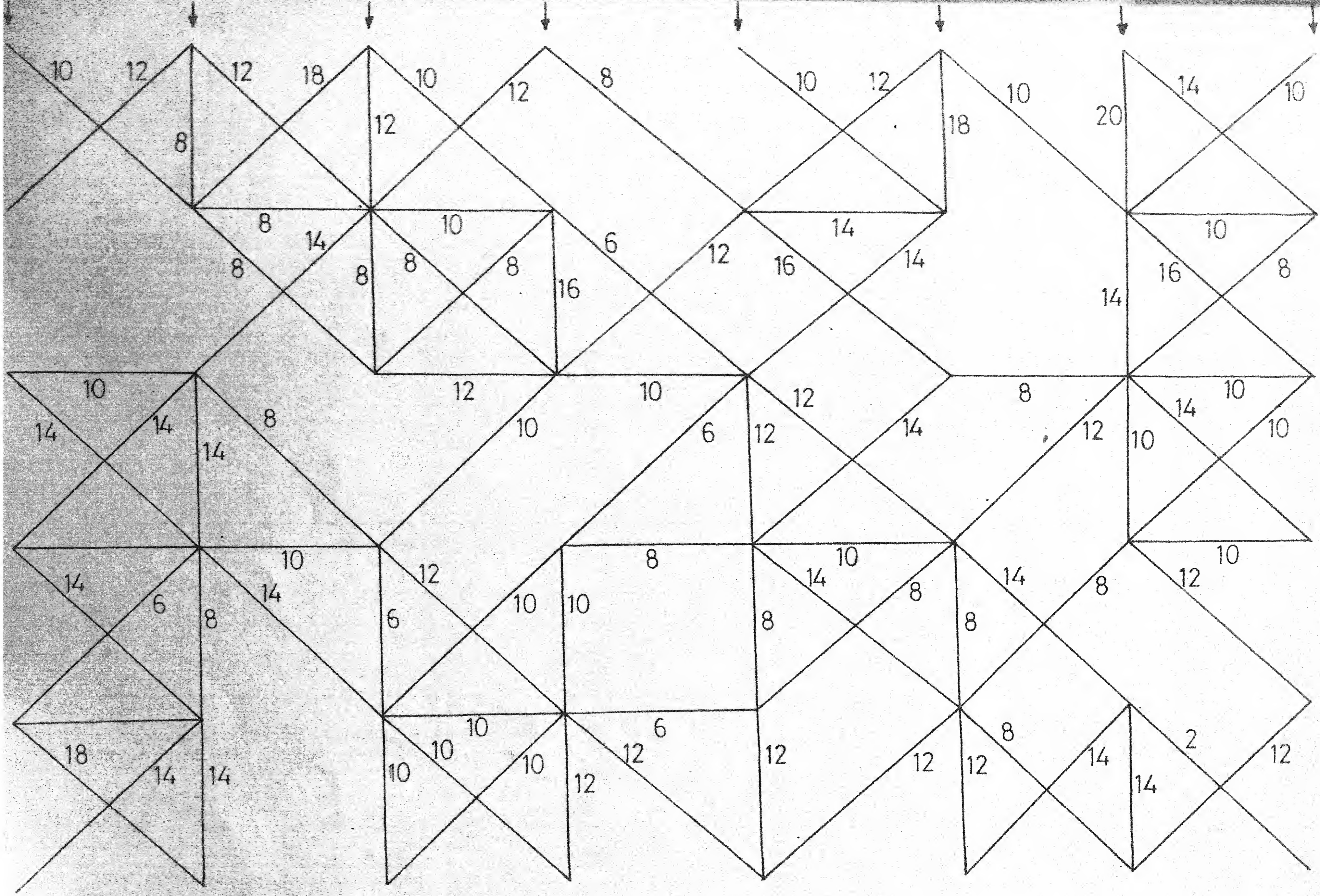

Fig.1 f - Network for poisson distribution (λ=10).

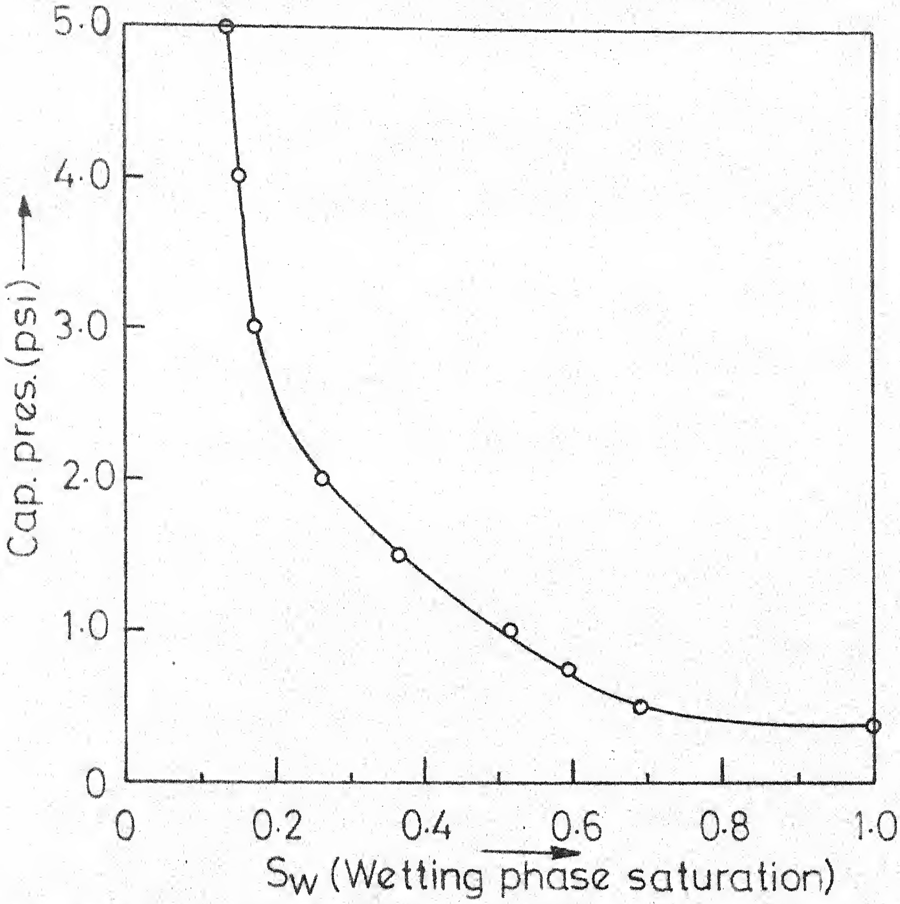

Fig.2a-P_c vs. S_w curve obtained from network I Fig.1a.

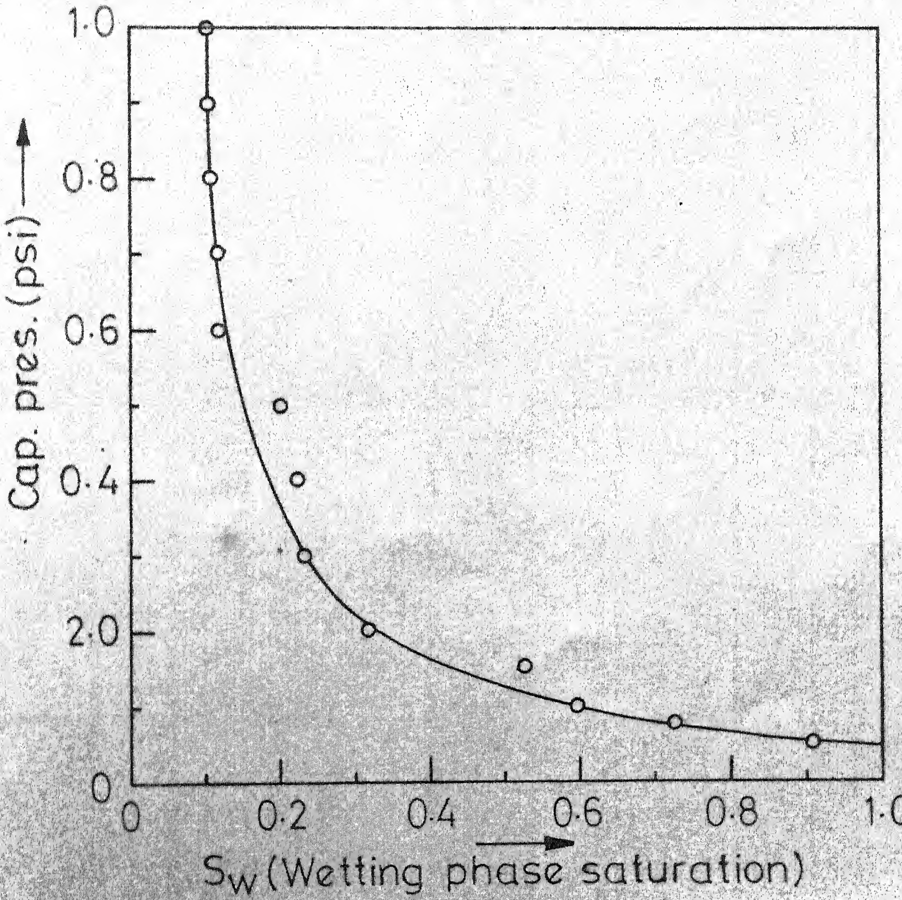

Fig.2b-P_c vs. S_w curve obtained from network II Fig.1b.

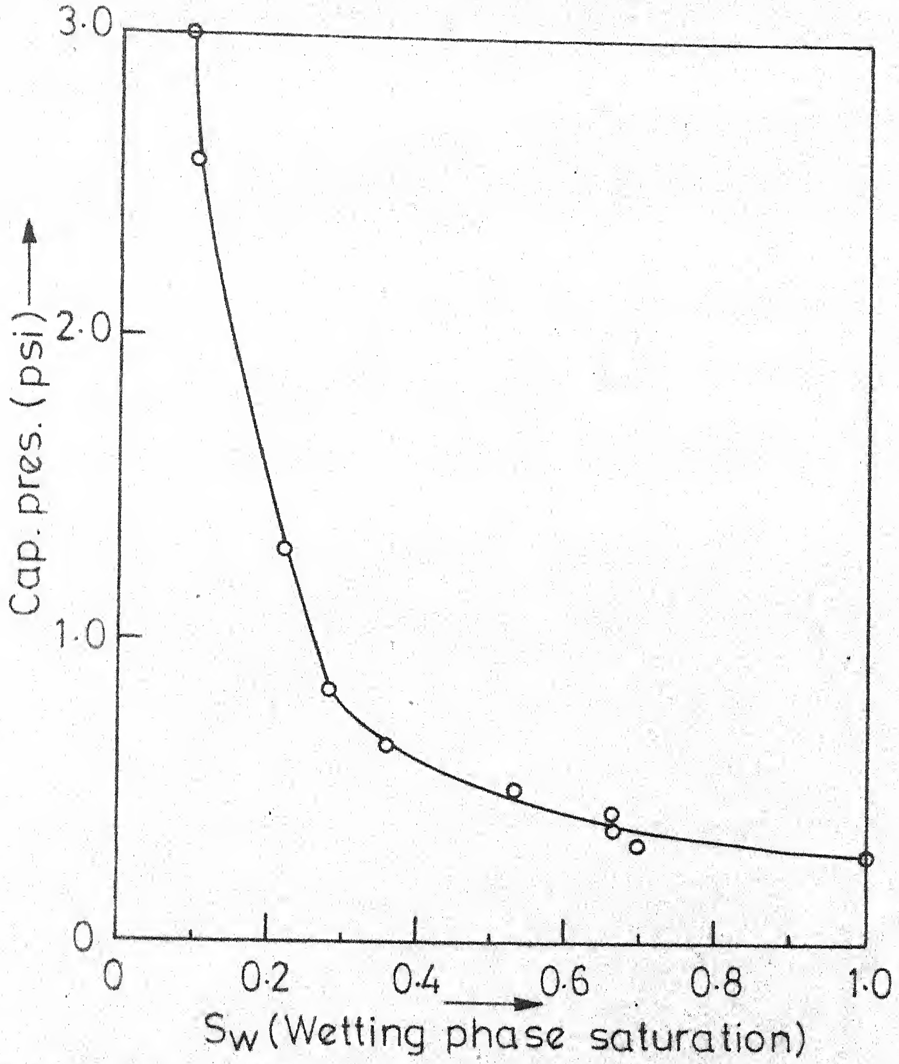

Fig.2c - P_c vs S_W curve for network III Fig.1c.

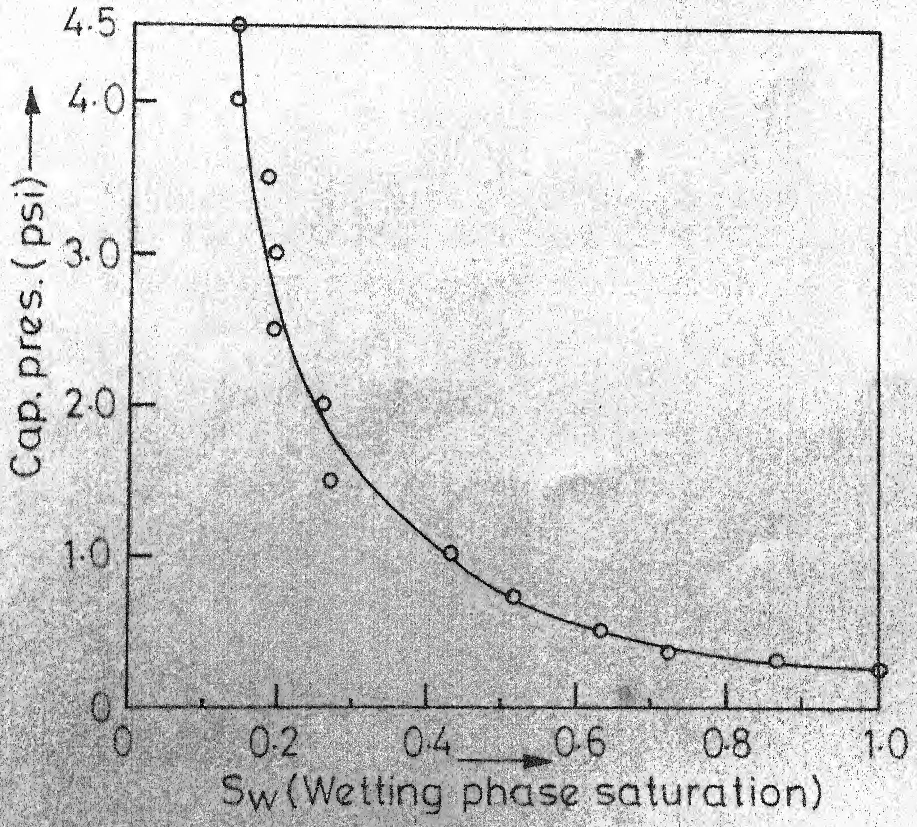

Fig.2d - P_c vs. S_W curve for network IV Fig.1d.

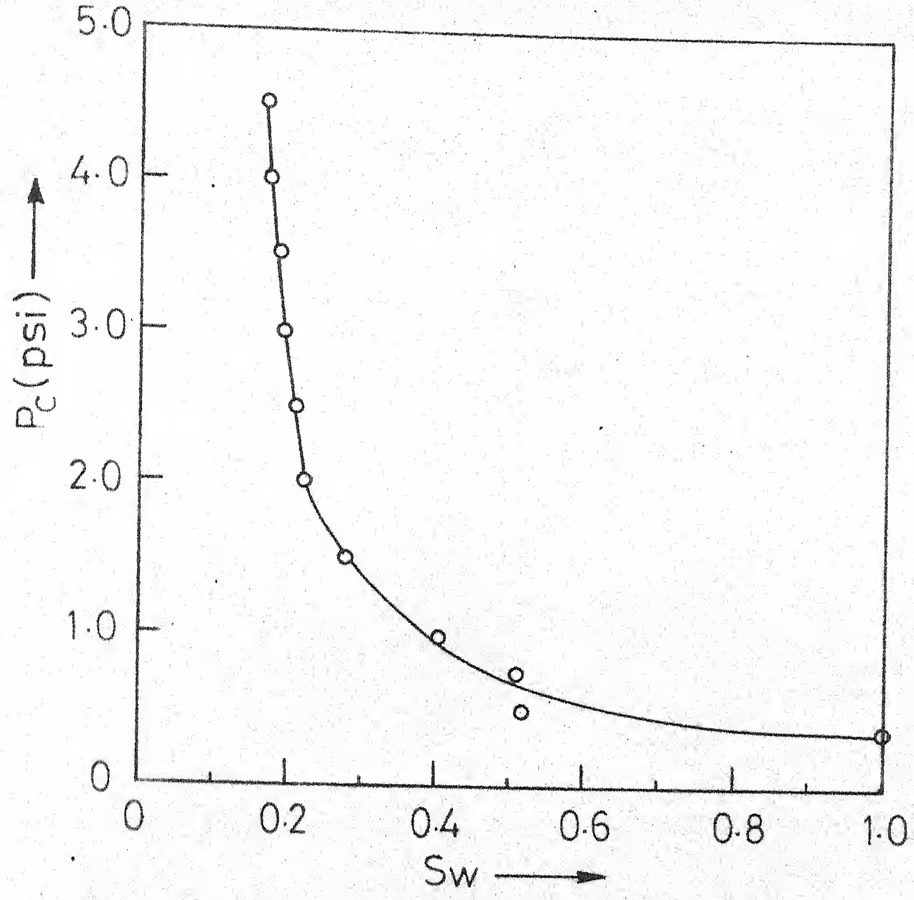

Fig. 2e - P_c vs. S_w curve for network V Fig. 1e.

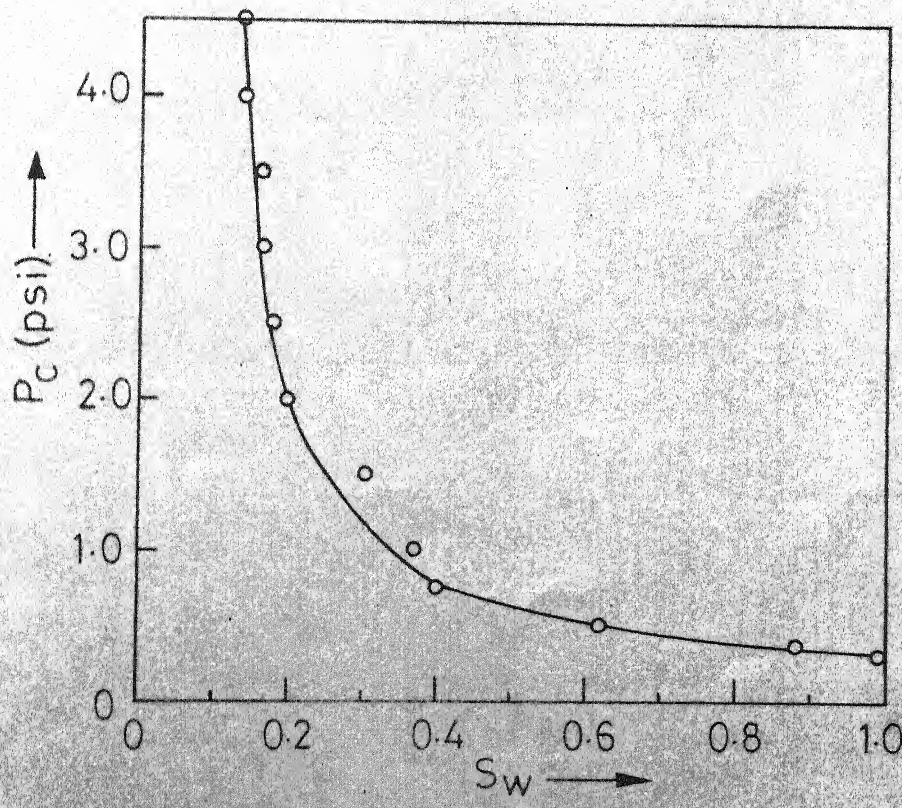

Fig. 2f - P_c vs. S_w curve for network VI Fig. 1f.

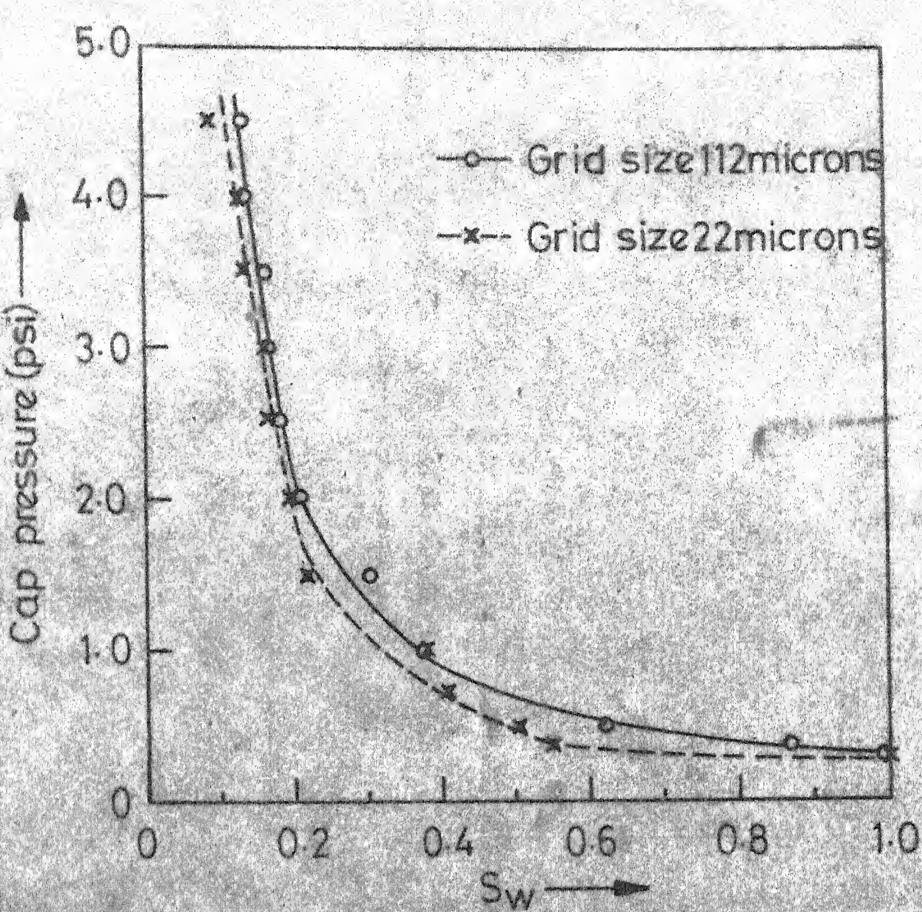

Fig.2g-Effect of grid size on P_c curve. Network VI.

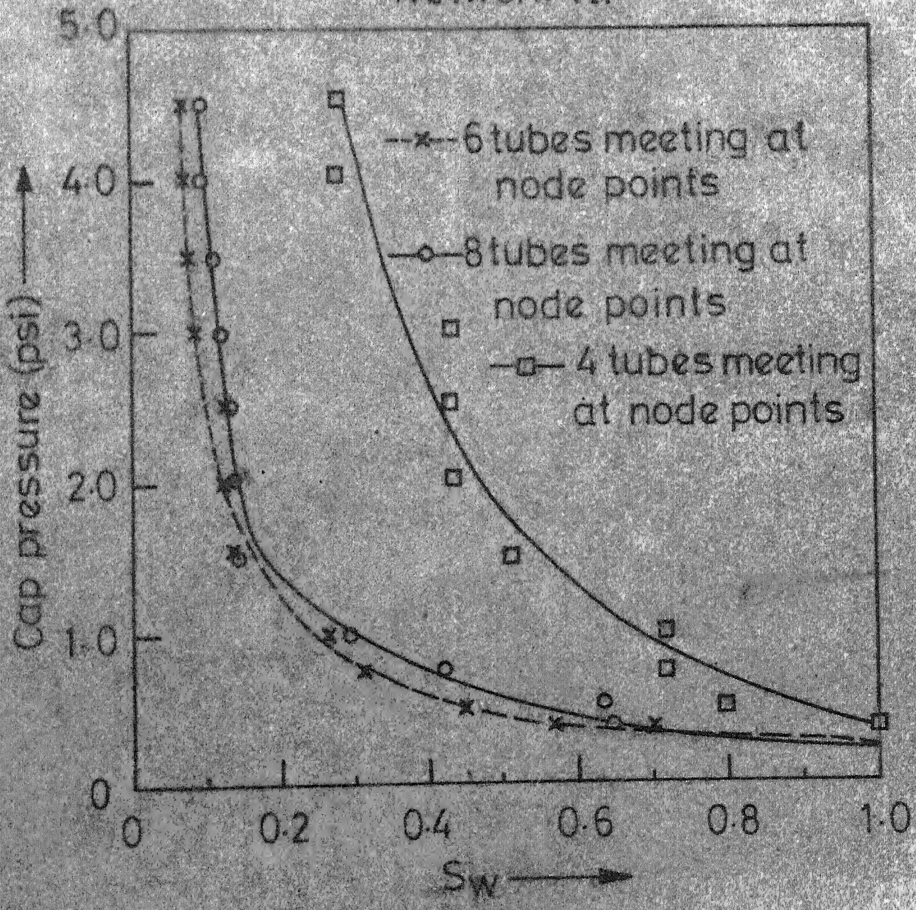

Fig.2h-Effect of network inter connections of P_c curve Network VI.

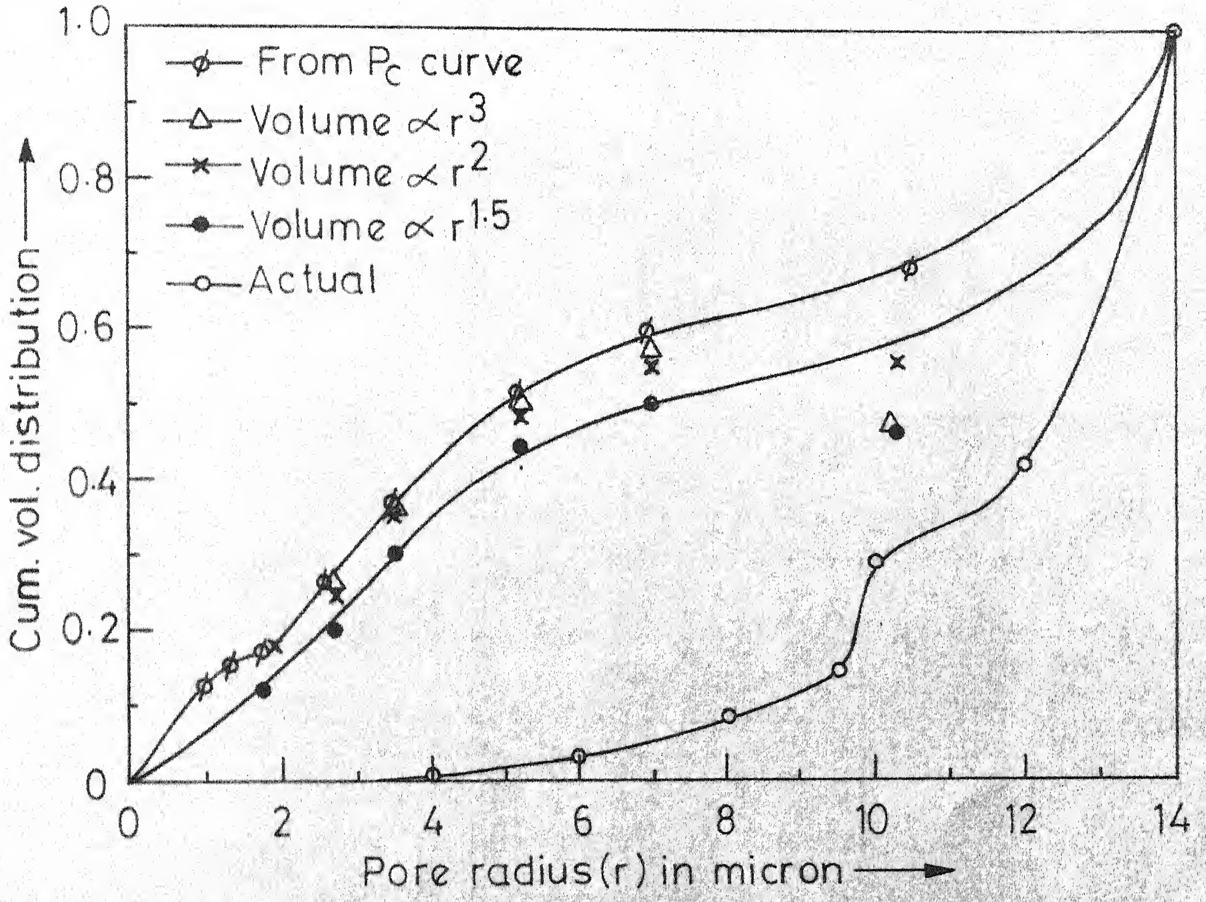

Fig.3a - Correction in volumetric distribution by Meyer's method. Network I.

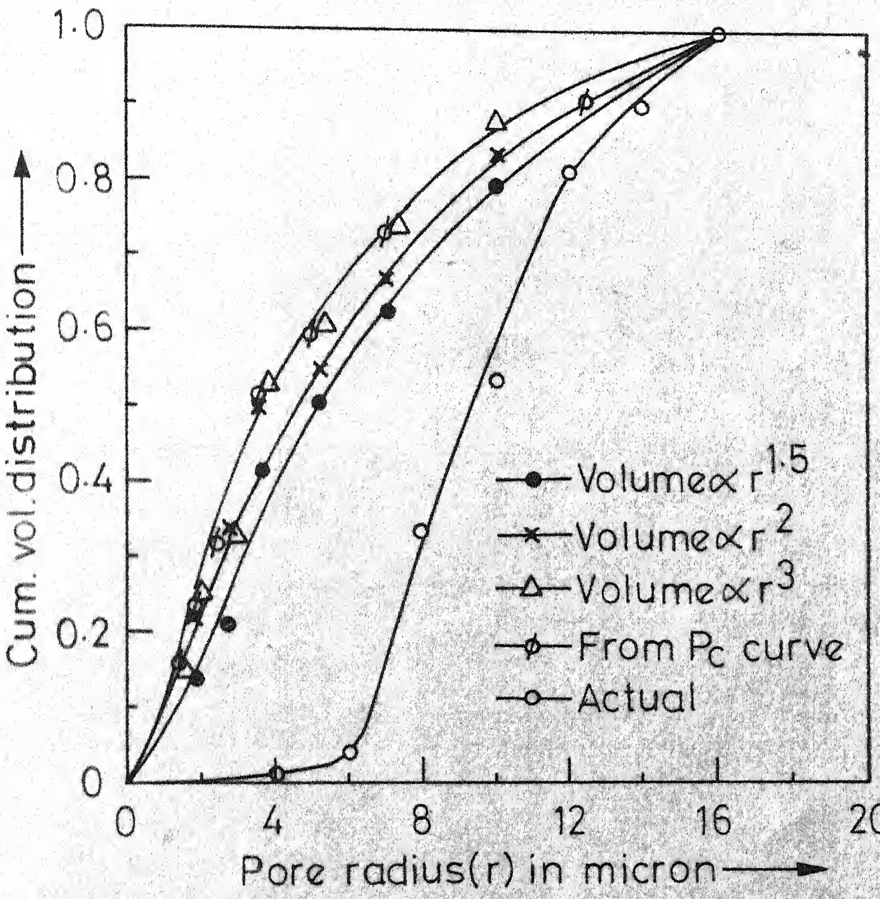

Fig.3b - Correction in volumetric distribution by Meyer's method. Network II.

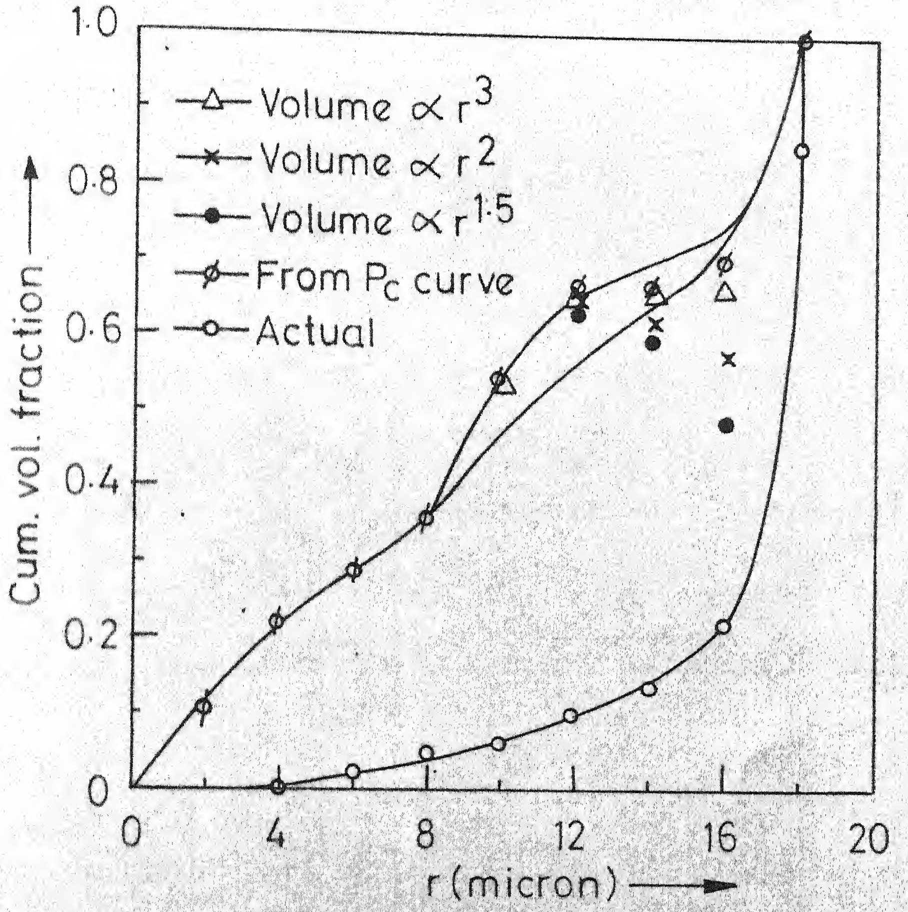

Fig. 3c - Correction in volumetric distribution by Meyer's method. Network III.

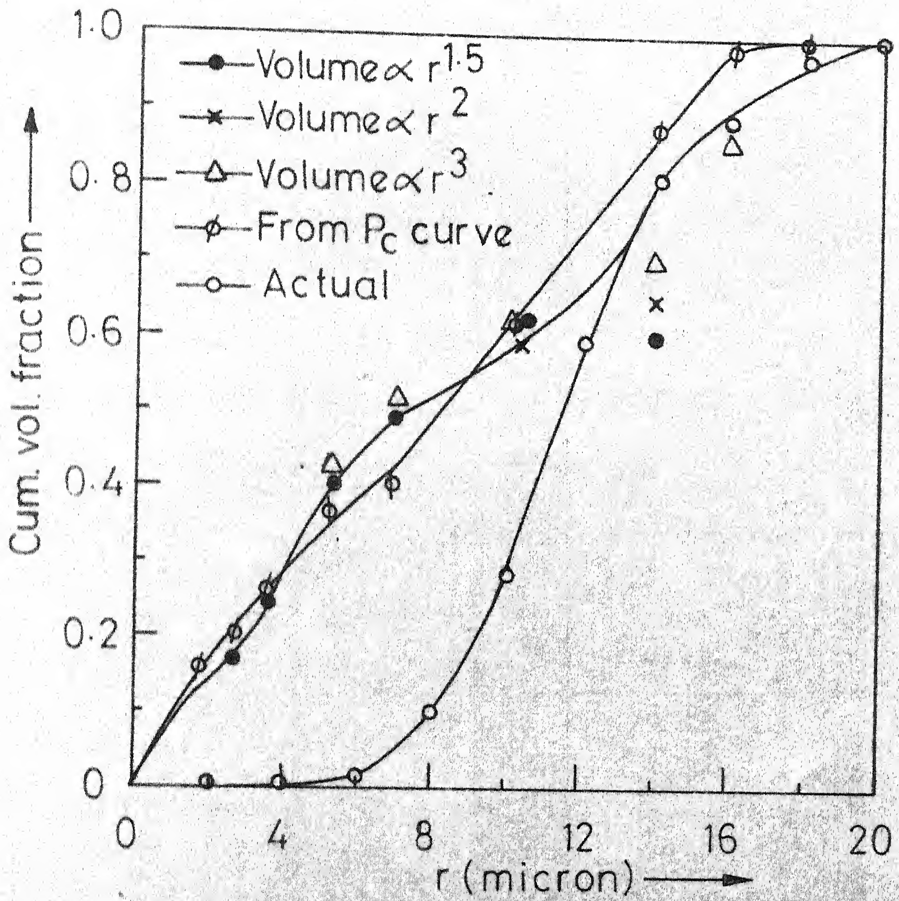

Fig. 3d - Correction in volumetric distribution by Meyer's method. Network IV.

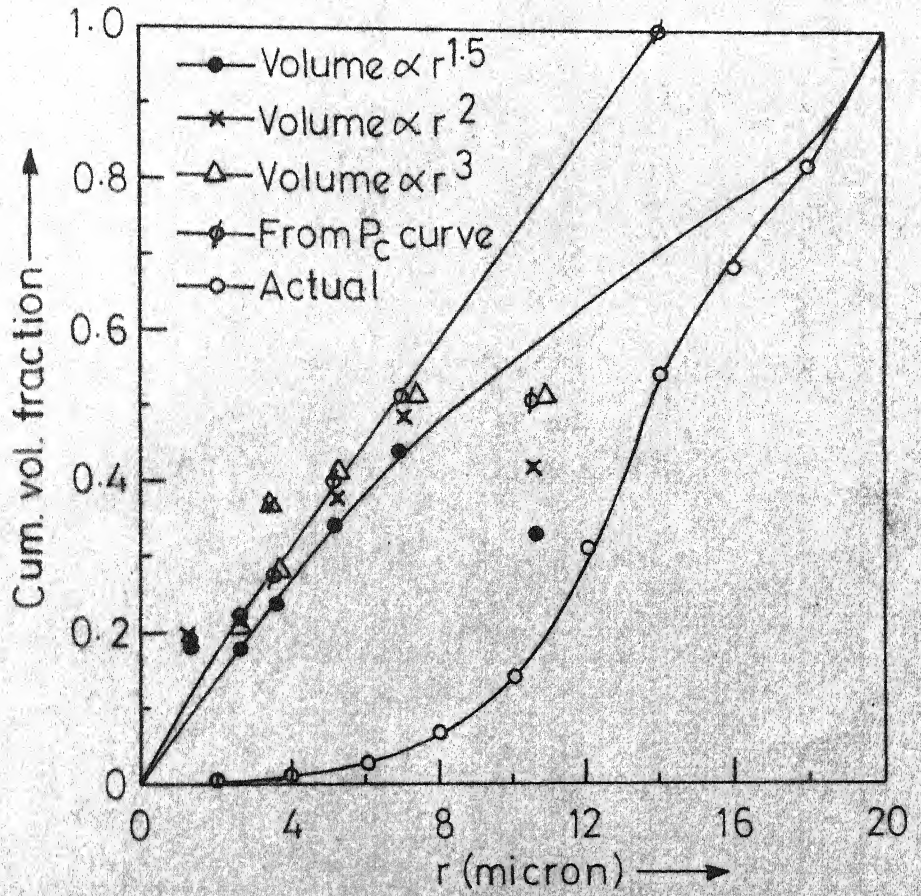

Fig. 3e-Correction in volumetric distribution by Meyer's method. Network V.

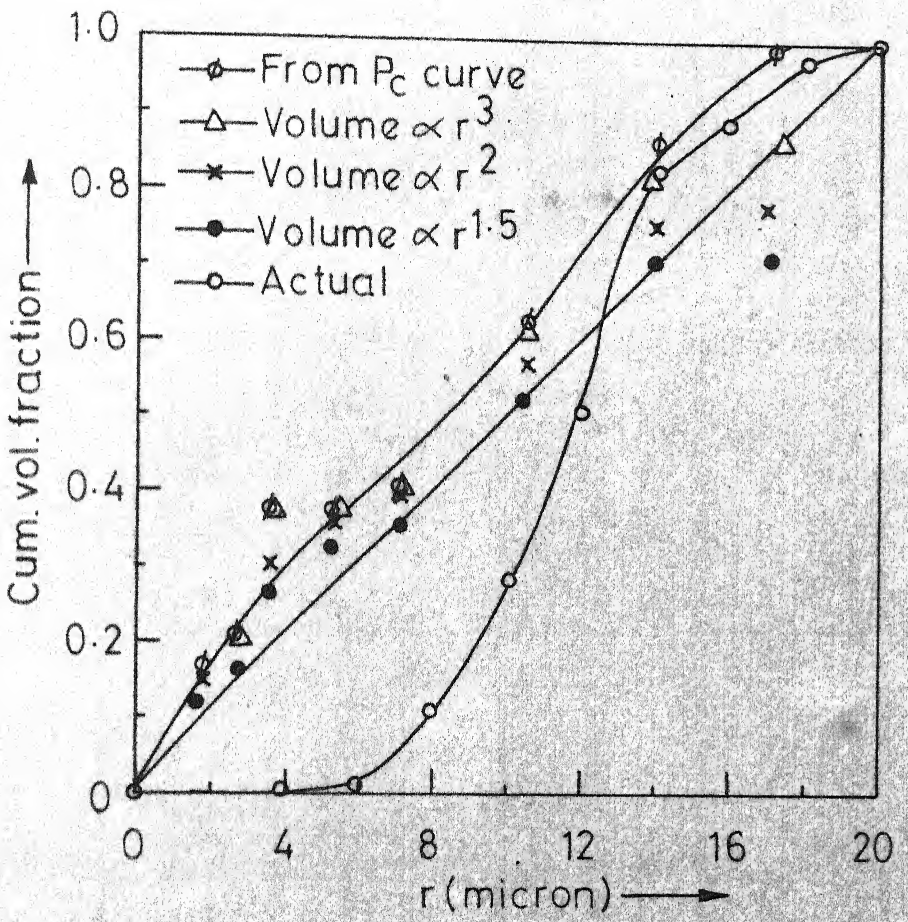

Fig. 3f - Correction in volumetric distribution by Meyer's method. Network VI.

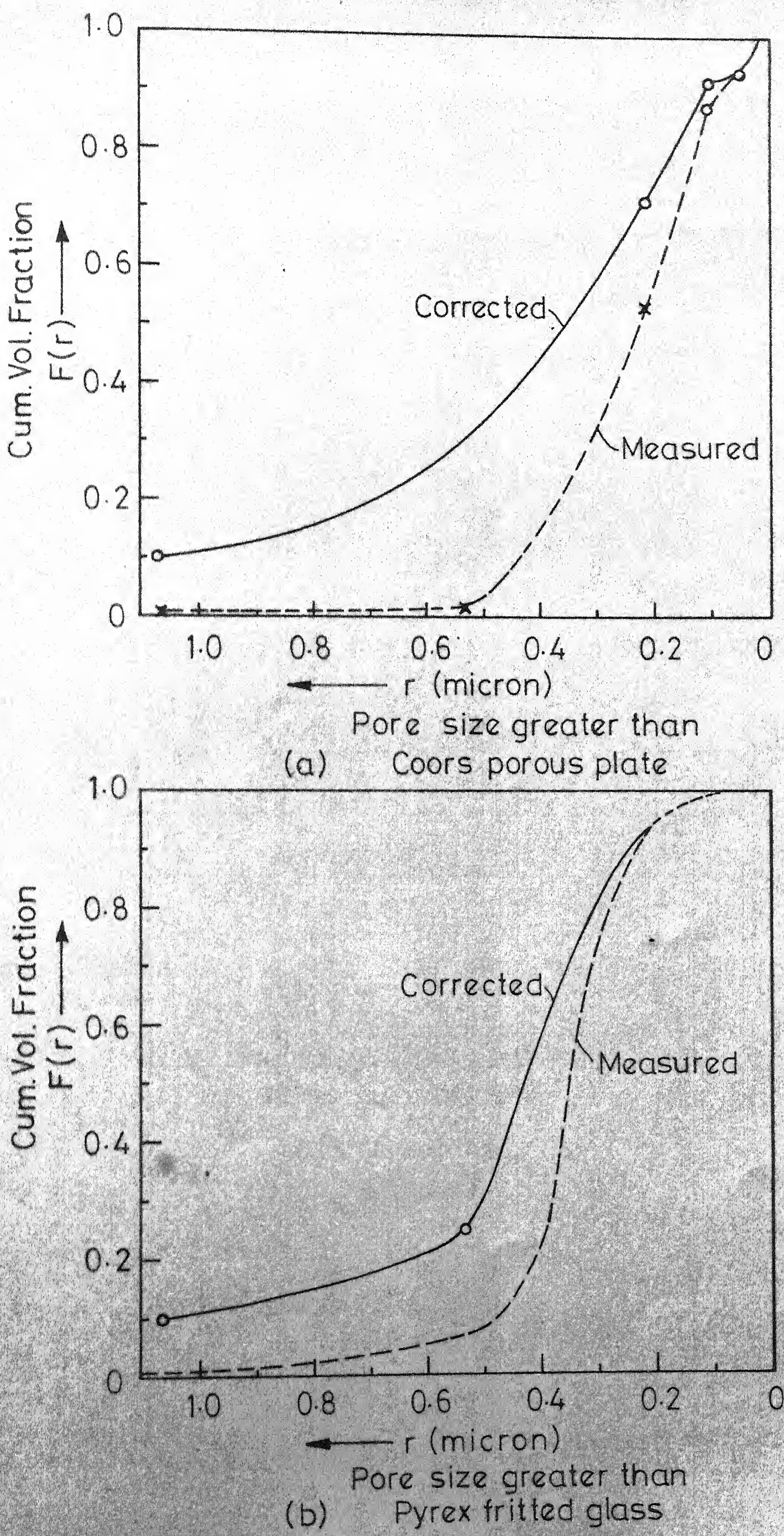

Fig. 4 - Correction applied to measured pore size distribution for 'ink bottle' effect. Table 4.

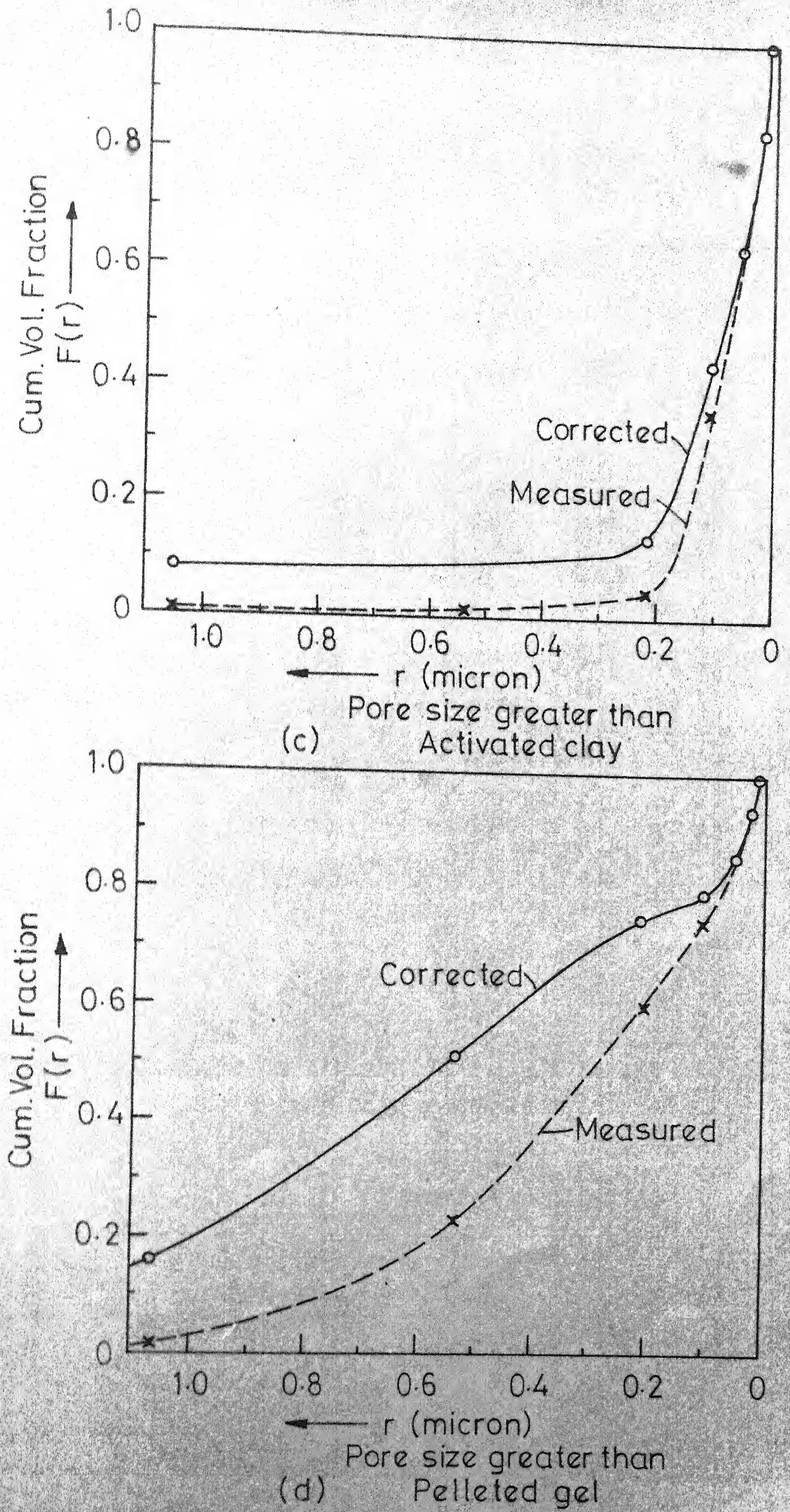

Fig. 4 - Correction applied to measured pore size distribution for 'ink bottle' effect. Table 4.

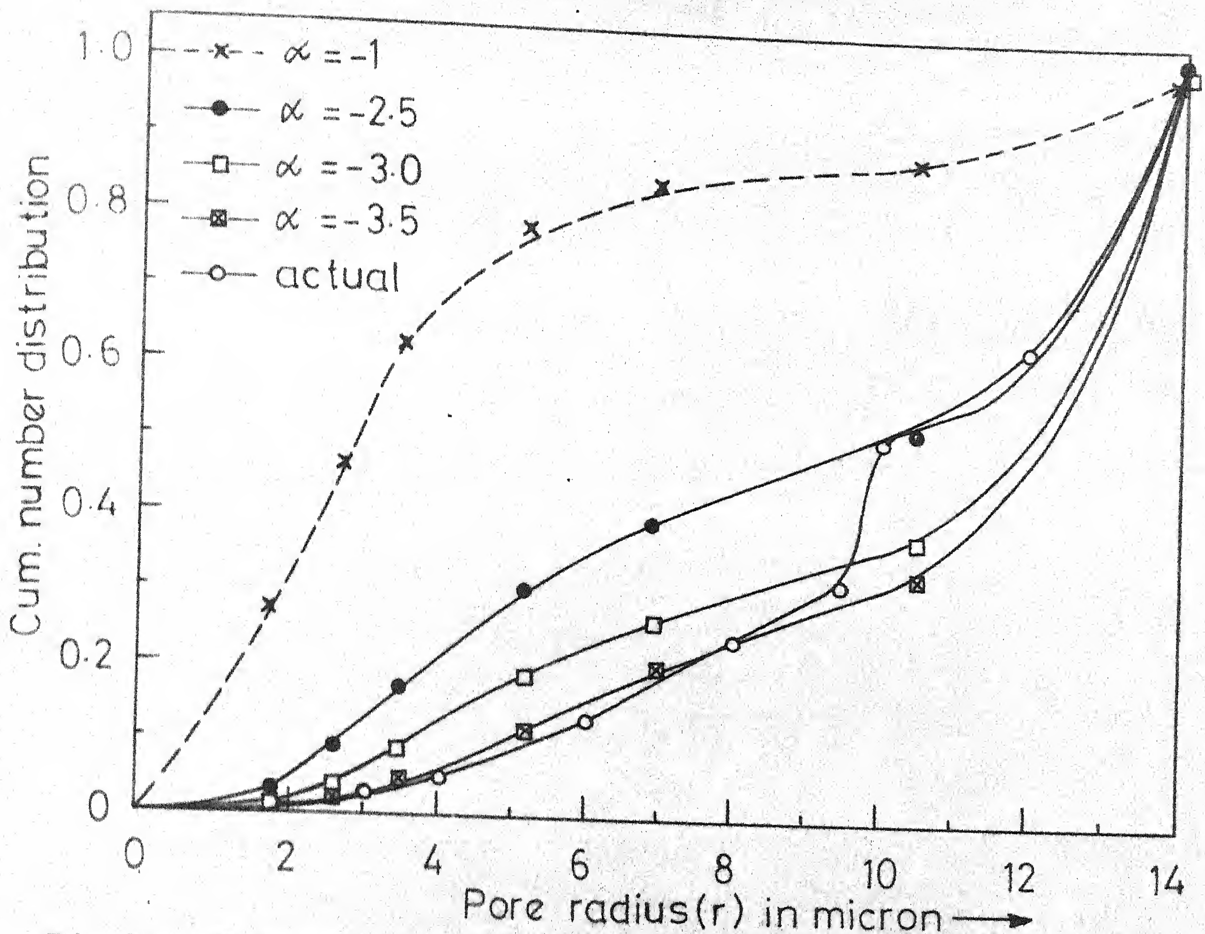

Fig. 5a - Comparison of calculated number distribution with actual network Fig.1a.

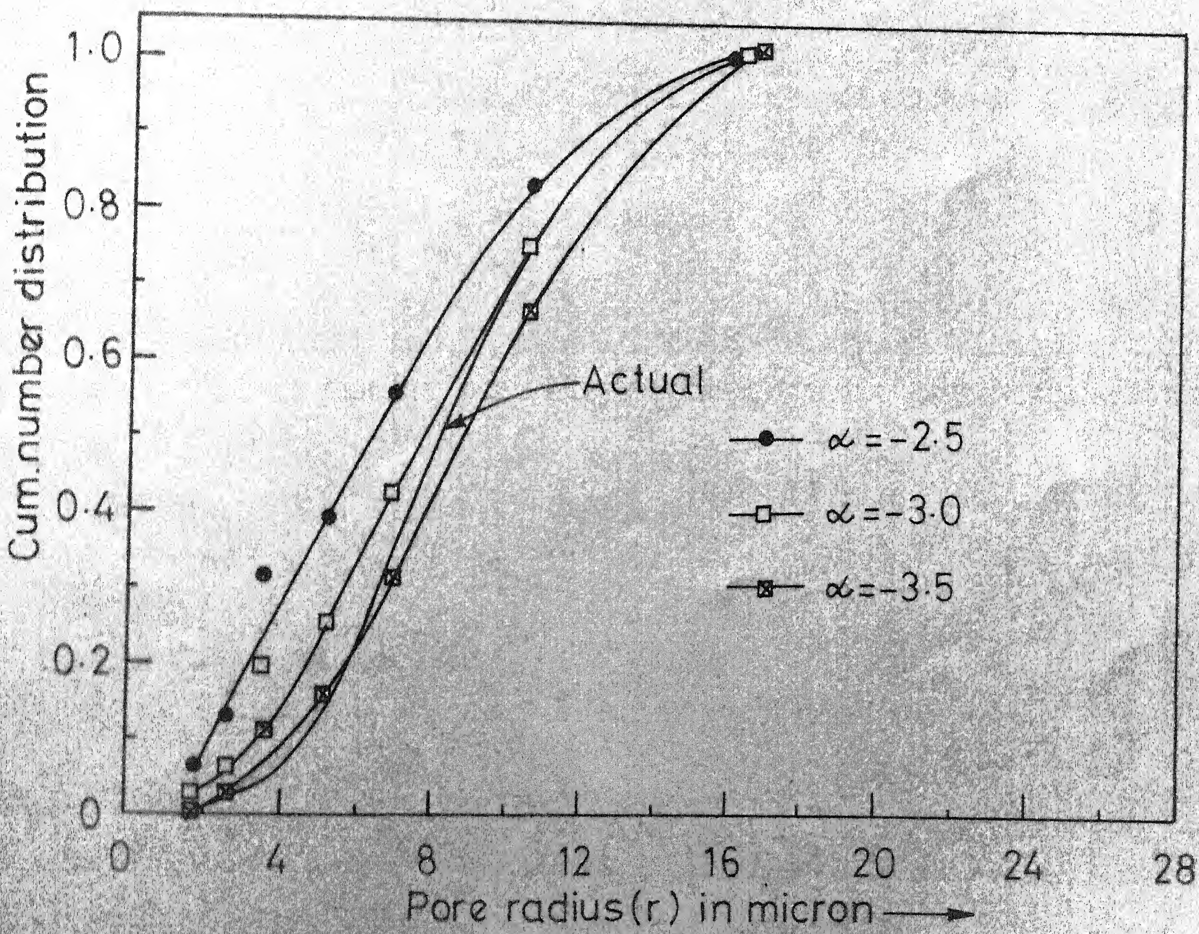

Fig 5b - Comparison of calculated number distribution with actual Network Fig 1b

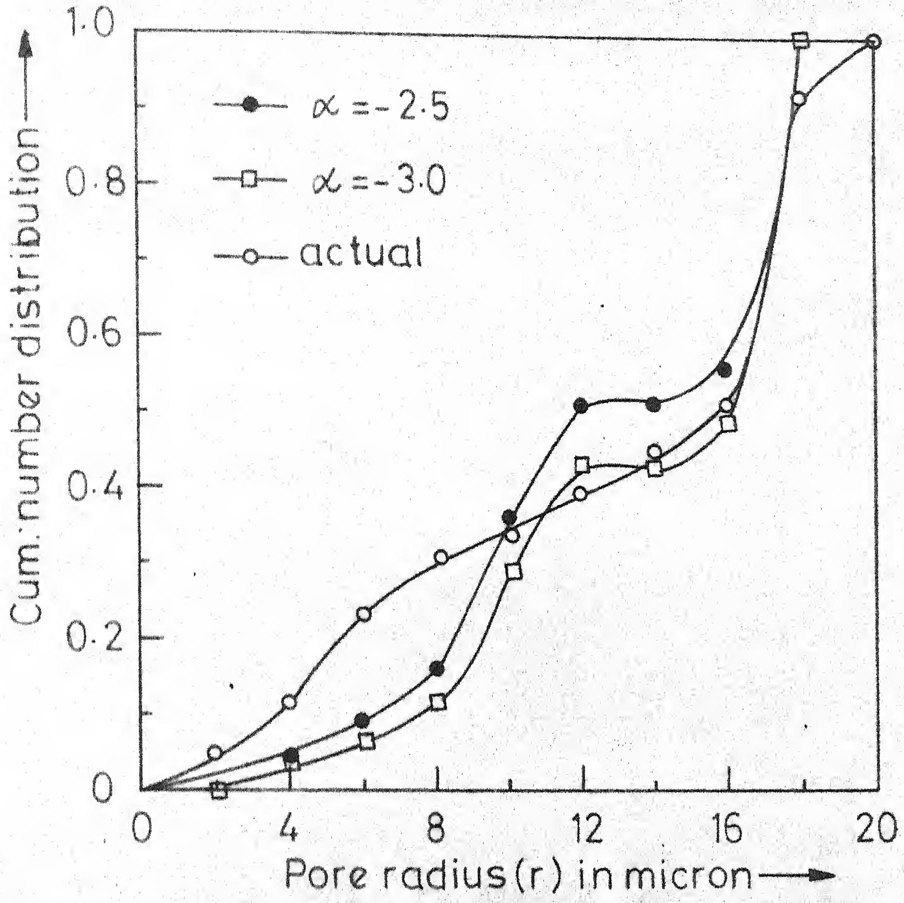

Fig. 5c - Comparison of calculated number distribution with actual. Network Fig. 1c.

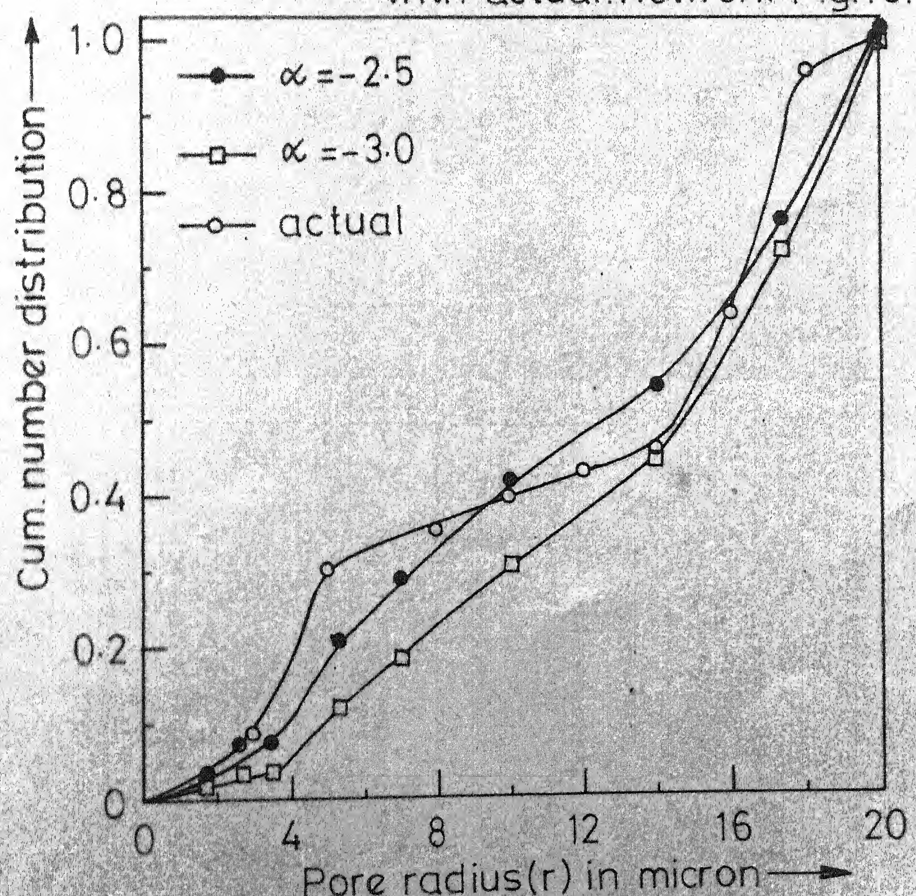

Fig. 5d - Comparison of calculated distribution with actual. Network Fig. 1d.

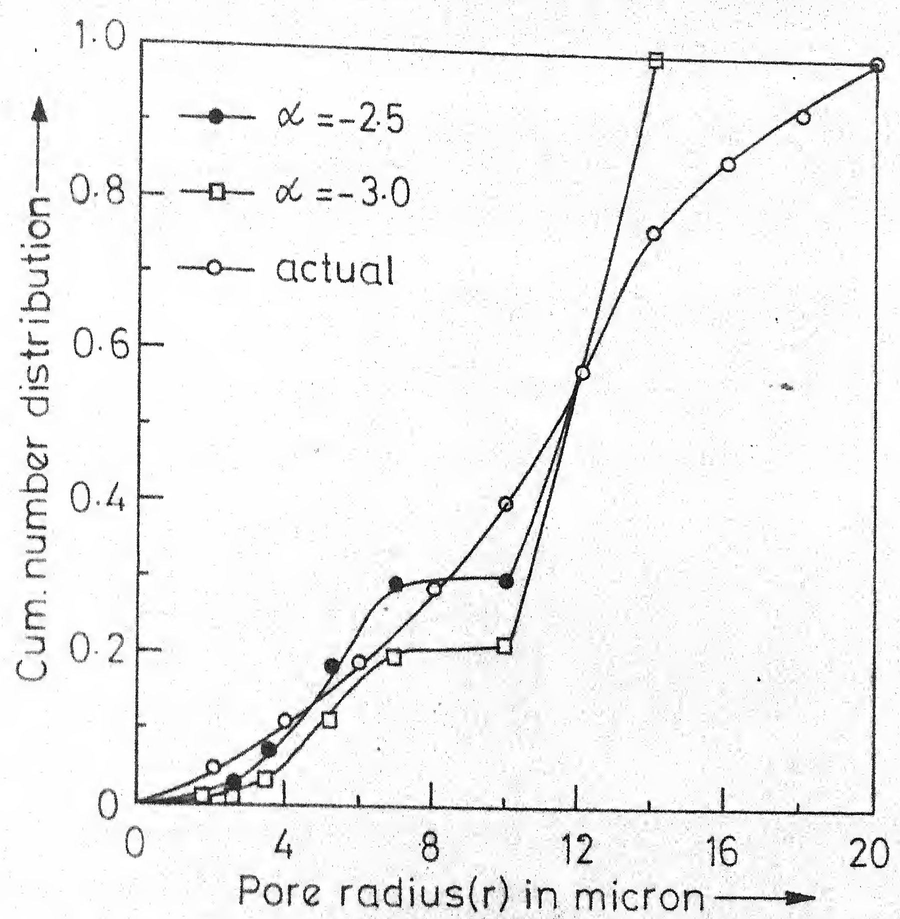

Fig. 5e-Comparison of calculated number distribution with actual. Network Fig.1e.

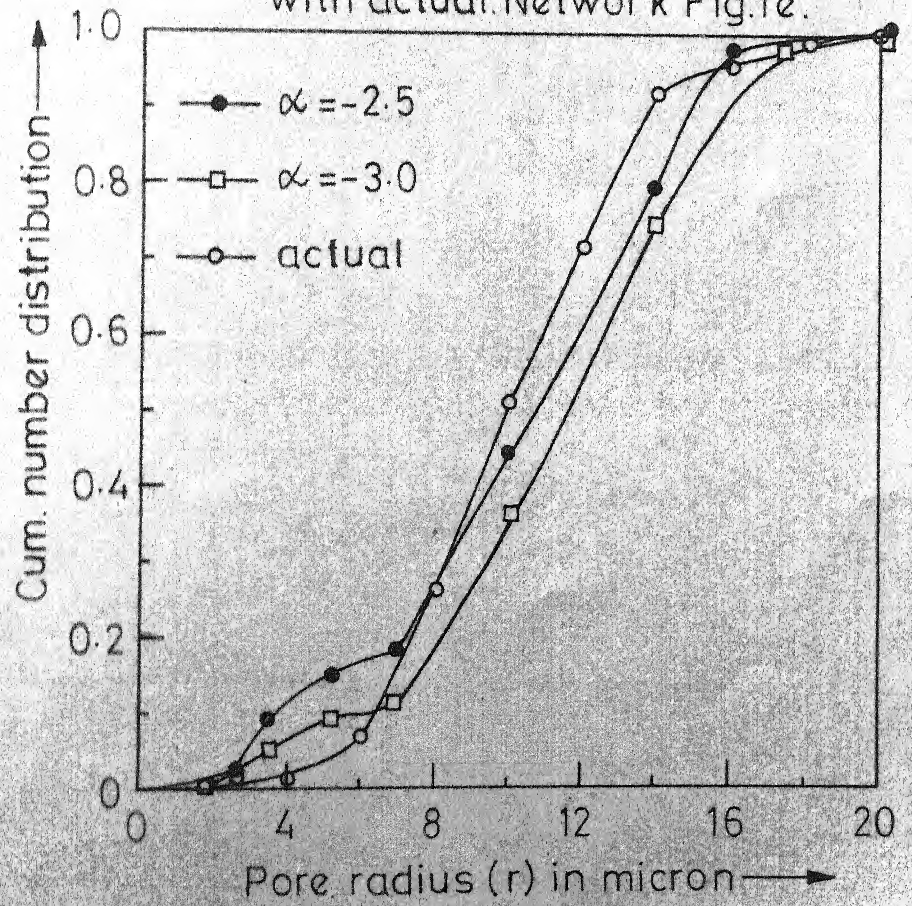

Fig.5f-Comparison of calculated number distribution with actual. Network Fig.1f.

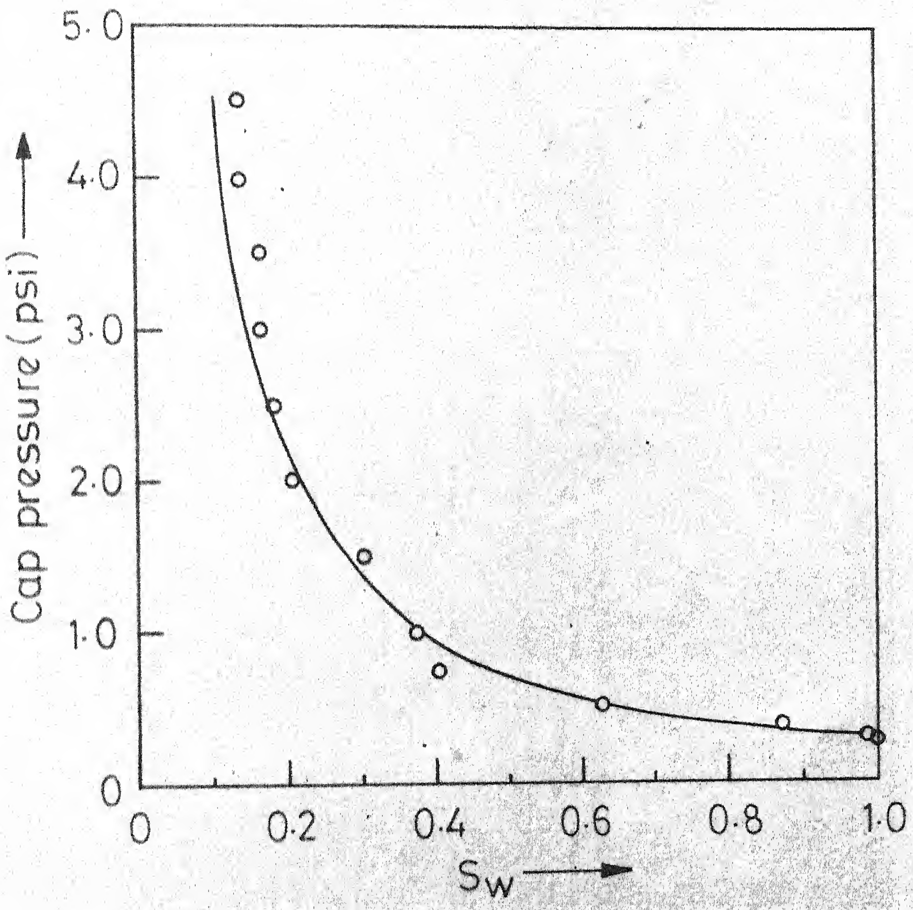

Fig. 6 -Least square fit of P_c data. Network VI.

TABLE 1

INPUT DATA FOR NETWORK I

Network size	8 x 6 node points
Grid Spacing	112 μ
Average opening at node points	25 μ
Interfacial tension	20 dynes/cm
Contact angle (non wetting fluid)	180°
Viscosity (non wetting fluid)	0.8 C_p
Viscosity (wetting fluid)	1.0 C_p
Trapping factor	0.20
Time Step (initial)	200 μ sec.

Pore Size Distribution:

Radius (μ)	Cum. Fraction (intended)	Cum. Fraction (adjusted)
0	0	0.25
3	0.0175	0.26328
4	0.047	0.28535
6	0.137	0.35234
8	0.27	0.45235
9.5	0.362	0.52189
10	0.576	0.68234
12	0.628	0.72150
14	1.0	1.0

***

TABLE 2

ARBITRARY DISTRIBUTION USED IN SIMULATION OF NETWORKS

Network	Pore-Size (μ)	Cum. Number Distribution
III	0.0	0.0
	2.0	0.0434
	4.0	0.1304
	6.0	0.2608
	8.0	0.3478
	10.0	0.3912
	12.0	0.4346
	14.0	0.4780
	16.0	0.5650
	18.0	0.9130
	20.0	1.0
IV	0.0	0.0
	3.0	0.075
	5.0	0.325
	8.0	0.400
	10.0	0.450
	12.0	0.500
	14.0	0.550
	16.0	0.650
	18.0	0.950
	20.0	1.0

****

TABLE 3

CAPILLARY PRESSURE DATA FOR SOME POROUS MATERIALS[25]

Materials	Volume of mercury(cc) injected per gm. of sample at pressure (psi) 100	200	500	1000	2000	5000	10,000 (Macro pore vol.)
Coors Porous Plate	0.001	0.003	0.093	0.152	0.162	0.172	0.173
Pyrex Fritted Glass	0.001	0.012	0.159	0.168	0.169	0.169	0.169
Activated Clay	0.001	0.002	0.009	0.071	0.123	0.166	0.195
Pelleted Gel	0.003	0.040	0.108	0.133	0.152	0.168	0.178

TABLE 4

COMPARISON OF EXPERIMENTAL PORE-SIZE DISTRIBUTION OBTAINED FROM MERCURY POROSIMETRY TO THAT CORRECTED BY MEYER'S METHOD

a) Coors Porous Plate

Pore-Size(Micron) greater than equal to	Cum. Fractional Pore Volume Exptl.	Cum.Fractional Pore Volume Corrected
1.066	0.00578	0.09797
0.533	0.01734	0.03578
0.213	0.53757	0.71379
0.1066	0.87861	0.92197
0.053	0.93642	0.93954
0.021	0.99422	0.99422
0.01060	1.00000	1.00000

b) Pyrex UF Fritted Glass

Pore-Size (Micron) Greater than equal to	Cum. Fractional Pore Volume Exptl.	Cum. Fractional Pore Volume Corrected
1.066	0.00592	0.10029
0.533	0.07101	0.24686
0.213	0.94083	0.94083
0.1066	0.99408	0.99408
0.05331	1.00000	1.00000
0.02132	1.00000	1.00000
0.01060	1.00000	1.00000

Table 4 (contd).

c) Activated Clay:

Pore-Size (Micron) Greater than equal to	Cum. Fractional Pore Volume Exptl.	Cum. Fractional Pore Volume Corrected
1.066	0.00513	0.08693
0.533	0.01026	0.01604
0.213	0.4615	0.14971
0.1066	0.36410	0.44945
0.05331	0.63077	0.63897
0.02132	0.85128	0.85128
0.01060	1.00000	1.00000

d) Pelleted Gel:

Pore-Size (Micron) Greater than Equal to	Cum. Fractional Pore Volume Exptl.	Cum. Fractional Pore Volume Corrected
1.066	0.1685	0.16701
0.533	0.22472	0.51417
0.2132	0.60674	0.75752
0.1066	0.74719	0.79563
0.05231	0.85393	0.85803
0.02132	0.94382	0.94382
0.01060	1.00000	1.00000

Table 5 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
	1.0	5.16	0.5956	0.594	0.542	0.500
	1.5	3.46	0.5261	0.5261	0.500	0.420
	2.0	2.60	0.3181	0.3181	0.282	0.2003
	3.0	1.73	0.2354	0.2354	0.221	0.1373
	4.0	1.29	0.2226	0.2226	0.202	0.1273
III	0.259	20.00	1.0	1.0	1.0	
	0.287	18.00	1.0	1.0	1.0	
	0.323	16.00	0.7016	0.664	0.573	0.490
	0.370	14.00	0.6655	0.661	0.622	0.600
	0.430	12.00	0.6655	0.665	0.649	0.630
	0.516	10.00	0.5383	0.539	0.534	-
	0.646	8.00	0.3541	0.3541	0.354	0.347
	0.862	6.00	0.2829	0.2829	0.283	0.271
	1.290	4.00	0.2213	0.2213	0.221	0.220
	2.580	2.00	0.1015	0.1015	0.101	0.101
	2.58	2.00	0.1015			
	3.00	1.73	0.1015			

Table 5 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
IV	0.259	20.00	1.0	1.0	1.0	1.0
	0.300	17.4	0.8657	–	–	–
	0.370	14.00	0.7195	0.702	0.649	0.602
	0.50	10.5	0.6296	0.630	0.612	0.585
	0.75	6.9	0.5143	0.5143	0.512	0.495
	1.0	5.16	0.4307	0.4307	0.428	0.409
	1.5	3.46	0.2650	0.2650	0.2650	0.255
	2.0	2.6	0.2603	0.2603	0.260	0.242
	2.5	–	0.1936	0.1936	0.192	0.170
	3.0	1.73	0.1936	0.1936	0.191	0.166
	3.5	–	0.1831	0.1831	0.18	0.154
	4.0	1.29	0.1400	0.1400	1.33	0.110
V	0.30	17.4	1.0			
	0.37	14.0	1.0	1.0	1.0	1.0
	0.50	10.5	0.5186	0.505	0.421	0.331
	0.75	6.9	0.5081	0.5074	0.479	0.438
	1.0	5.16	0.4032	0.4032	0.380	0.343
	1.5	3.46	0.2763	0.2763	0.269	0.234

Table 5 (contd)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
	2.0	2.6	0.2206	0.2206	0.210	0.171
	3.0	1.73	0.1900	0.1900	0.190	0.190
	4.0	1.29	0.1724	0.1724	0.172	0.172
VI	0.259	20.00	1.0	1.0	1.0	1.0
	0.30	17.4	0.9882	0.852	0.777	0.717
	0.37	14.0	0.8718	0.812	0.751	0.707
	0.50	10.5	0.6216	0.617	0.570	0.520
	0.75	6.9	0.4009	0.401	0.390	0.352
	1.0	5.16	0.3703	0.3703	0.358	0.322
	1.5	3.46	0.3702	0.3702	0.298	0.267
	2.5	2.6	0.2077	0.2077	0.202	0.163
	3.0	1.73	0.1653	0.1653	0.155	0.116
	4.0	1.29	0.1352	0.1352	0.122	0.089

TABLE 6

CALCULATION OF NUMBER CUM. DISTRIBUTION FROM P_c DATA OF NETWORKS BY FATT'S MODEL WITH MODIFIED EXPONENT

Network	P_c	r	S_w	Computed Number Distribution		
				$\alpha = -2.5$	$\alpha = -3.0$	$\alpha = -3.5$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
I	0.37	14.00	1.0	1.0	1.0	1.0
	0.50	10.5	0.6920	0.5247	0.3854	0.33
	0.75	6.9	0.5948	0.3962	0.26236	0.201
	1.00	5.16	0.5155	0.3086	0.1883	0.116
	1.50	3.46	0.3685	0.1716	0.0904	0.047
	2.0	2.60	0.2603	0.0310	0.011	0.0044
II	0.324	16.0	1.0	1.0	1.0	1.0
	0.5	10.5	0.91	0.831	0.752	0.667
	0.75	6.9	0.729	0.558	0.424	0.313
	1.0	5.16	0.596	0.390	0.258	0.161
	1.5	3.46	0.526	0.315	0.195	0.112
	2.0	2.6	0.318	0.130	0.064	0.029
	3.0	1.73	0.235	0.067	0.027	0.010
III	0.287	18.00	1.0		1.0	1.0
	0.323	16.00	0.70		0.485	0.560
	0.370	14.00	0.666		0.43	0.510
	0.430	12.00	0.666		0.43	0.510
	0.516	10.00	0.538		0.287	0.358

Table 6(contd)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
	0.646	8.00	0.354		0.1184	0.16
	0.862	6.00	0.283		0.0678	0.090
	1.290	4.00	0.221		0.0365	0.042
	2.580	2.00	0.1015		0.0	0.0
IV	0.259	20.00	1.0	1.0	1.0	
	0.30	17.4	0.8657	0.76	0.72	
	0.37	14.0	0.7195	0.54	0.44	
	0.5	10.5	0.6296	0.418	0.305	
	0.75	6.9	0.5143	0.286	0.180	
	1.0	5.16	0.431	0.204	0.118	
	1.5	3.46	0.265	0.07	0.030	
	2.0	2.6	0.260	0.067	0.029	
	3.0	1.73	0.194	0.027	0.010	
V	0.37	14.0	1.0	1.0	1.0	
	0.50	10.5	0.5186	0.215	0.30	
	0.75	6.9	0.5081	0.202	0.29	
	1.00	5.16	0.4032	0.116	0.182	
	1.50	3.46	0.2763	0.035	0.07	
	2.0	2.6	0.2206	0.0128	0.03	
	3.0	1.73	0.190	0.0043	0.0115	

Table 6 (Contd.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
VI	0.259	20.0	1.0	1.0	1.0	
	0.30	16.0	0.988	0.98	0.977	
	0.37	14.0	0.8718	0.795	0.746	
	0.50	10.5	0.6216	0.4428	0.360	
	0.75	6.9	0.4009	0.1818	0.1144	
	1.00	5.16	0.3703	0.1514	0.091	
	1.50	3.46	0.3029	0.095	0.054	
	2.0	2.6	0.2077	0.0275	0.017	
	3.0	1.73	0.1653	0.002	0.0056	

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APPENDIX A

NETWORK MODEL: FLOW COMPUTATION

Pressure Computation:

Assuming that flow in the pore channels of a porous system is essentially viscous in nature (Re $<$ 75), Poiseuille's law of viscous flow could be applied for flow computation in each tube of the network. For single phase flow in a cylindrical tube of length l_i and radius r_i, the expression for flow rate, q_i is given as:

$$q_i = \frac{\pi r_i^4}{8\mu} \cdot \frac{\Delta P}{l_i} \tag{A.1}$$

or

$$q_i = K_i \; \Delta P_i$$

where ΔP_i is the pressure differential causing flow in the ith tube. For multiphase flow K_i and ΔP_i may be modified depending upon the relative proportion of the different fluids present and the nature of the flow regime respectively. Knowing total fluid conductivity, K_i, of each tube and maintaining total volumetric balance a Kirchoff type equation can be written for each node point of the network:

$$\sum_{\substack{s=1,8 \\ k=i-1,i+1 \\ l=j-1,j+1 \\ (i,j)\neq(k,l)}} K_s \left[(P_{i,j} - P_{k,l}) + P_c \right] = 0 \tag{A.2}$$

Knowing the values of K_s, P_c and the pressure at the boundaries, the set of simultaneous algebraic equations can be solved by Gauss-elimination technique.

Capillary Pressure:

Capillary pressure, P_c, is applicable only to those pores which undergo displacement flow. For single phase, slug or annular flow regimes, capillary pressure is essentially zero. In this computation P_c is taken as equal to the pressure required to squeeze an fluid/fluid interface from a mode point opening (radius r_{no}) to a tube of radius r_i(r_{no} r_i). For a tube of triangular cross-section

$$P_c = 1.78\ \gamma \cos\theta \left(\frac{1}{r_{no}} - \frac{1}{r_i}\right) \qquad (A.3)$$

where γ = interfacial tension and θ is the contact angle which in our case is the receding contact angle.

Flow Behaviour in a Single Tube:

i) Single Phase Flow:

The total volumetric flow rate through a tube of triangular (equilateral) cross section, with the radius of the inscribed circle, r, viscosity of the fluid μ, and pressure gradient $\Delta P/\Delta l$, is

$$q = \frac{1.35}{\sqrt{3}}\ \frac{r^4}{\mu}\ \frac{\Delta P}{\Delta l} \qquad (A.4)$$

ii) Annular Flow:

We used modified Yuster relationship as suggested

by Singhal[22] for flow computation.

$$q_w = \frac{1.35}{\sqrt{3}} \frac{r^4}{\mu_w} \frac{\Delta P}{\Delta l} S_w^2 \qquad (A.5)$$

$$q_n = \frac{1.35}{\sqrt{3}} \frac{r^4}{\mu_n} \frac{\Delta P}{\Delta l}\left[\left(2S_n \frac{\mu_n}{\mu_w} + S_n^2\left(1-2\frac{\mu_n}{\mu_w}\right)\right)\right] \qquad (A.6)$$

where S denotes saturation and subscripts w and n denote wetting and and non-wetting phase respectively.

(iii) Slug Flow:

Total flow rate is given by

$$q_{tot} = \frac{1.35}{\sqrt{3}} \frac{r^4}{(\mu_w l_w + \mu_n l_n + 6a\mu_w)} \Delta P \qquad (A.7)$$

where a is the side of the triangular cross section.

(iv) Displacement Flow:

$$q_{tot} = \frac{1.35}{\sqrt{3}} \frac{r^4}{(\mu_w l_w + \mu_n l_n)} \left[\Delta P \pm P_c\right] \qquad (A.8)$$

<u>Selection of Tube for Flow Change:</u>

Depending on the availability of fluids at a node point, transition between flow regimes will occur. In many instances, channels leaving a node point may be capable of carrying more of a particular phase (fluid) than is available at that time. In such cases, saturation and flow regime changes in the tubes will have to occur to unload all available fluids. A table of possible transition between flow regimes is given in Table A-1. Some times there may exist more than one pore which might be undergoing flow in the regime to be altered. Selection of tubes

for flow changes in such cases is done by Monte-Carlo method with a bias for flow capacities of the competing tubes.

General Scheme for Flow Computation:

Words in block capital letters are subroutine name referred to in the program listing.

The network is generated in the program by SIMU with specified pore-size distribution and grid size. This subroutine also computes the volume of the pores connected to each node point and flow conductivities to the two fluids. Other data; fluid viscosities, interfacial tension, pressure differential across the model and contact angle, are read in the main program CALC. The radius of the opening at the node points, r_n, is chosen to be slightly larger than the largest tube radius of the network.

The next step is to determine the pressure distribution in the model. Pressure at each node point is computed by solving the system of equation A-2 by PRSOL through SOLVE. Apart from updating the conductivities of each tube after every time step, SOLVE also immobilizes those tubes which may cause outflow from the first row and inflow from the last row. Also, those tubes, whose capillary pressure is greater than the pressure differential available and are oppositely directed, are blocked by the action of trapping factor. When a tube is blocked its conductivity is set equal to zero and the system of equations A-2 is solved. This is repeated till no more

tubes are blocked. While calculating P_c for tubes in the first row, the node point opening is assumed to be infinite. For other rows the specified value of r_n is used for the calculation.

The total outflow of each phase (fluid) from each node point is calculated under the existing pressure distribution by FLOW. Outflow from a tube is entered as inflow to the connected node point by COND(1). The imbalance between inflow and outflow of a particular phase at a node point is corrected by CHANGE which also effects the flow changes necessary for this correction. The capillary pressure and flow conductivities for the corrected flow distribution is computed by COND(2) and stored. Outflow from the model is obtained by adding together the inflow to the last row of node points. The volume of the fluid left in the model is computed to evaluate the saturation. This process is repeated till the equilibrium wetting phase saturation in model is obtained for that pressure drop.

Steps of Computation:

(i) Call SIMU to simulate the network model. Assign tube sizes, locations etc. Calculate the volume of each tube, its conductivity to displacing and displaced fluids.

(ii) Call SOLVE to update the conductivities through COND(2) and solve the system of equations A.2 by PRSOL to evaluate the absolute pressure at each node point. In case some of the tubes are blocked, call COND(1) to zero the

conductivity of those tubes and again call PRSOL to solve the systemof equation A-2. Repeat till no more tubes are blocked.

(iii) Choose node points in descending order of absolute pressure and call FLOW to calculate outflow of each fluid from each tube and node point.

(iv) Calculate imbalance at each node point to test whether overall material balance of incoming and outgoing fluids is satisfied.

(v) Imbalance in the material balance of each phase is removed by assigning the excess incoming phase to various tubes by Monte Carlo method through CHANGE without forcing flow change in the tubes.

(vi) Assign outflow from each tube as the inflow to the connected down-stream node points.

(vii) In case of back flow, calculate inflow to those tubes and node points in FLOW. If there is any imbalance either in total fluid at the connected node points or imbalance in any phase in any tube, call CHANGE to assign the differential volume to various tubes.

(viii) Calculate outflow from the model by adding the inflow to each node points in the last row of the network.

(ix) Calculate total fluid volume left in the model by adding the volume of the fluid in each tube at the end of the time interval.

(x) Calculate the saturation for each phase.

(xi) Repeat steps (i) to (x) till there is practically no change in the total outflow from the model in the successive time steps (less than 1% of the outflow in the first time step) for the same ΔP.

(xii) Test whether the sum of the cumulative outflow and the volume of fluid remaining in the network for each fluid at the end of every time step is constant.

(xiii) Repeat the sequence of operations with higher ΔP, to get the value of equilibrium S_w (wetting phase saturation) for different P_c. Thus P_c curve is generated.

TABLE A-1

TRANSITION BETWEEN FLOW REGIMES

Flow Regimes To / From	Single Phase	Displacement	Slug	Annular
Single Phase	x	1*	1*	1
Displacement	2	x	–	–
Slug	–	–	x	1
Annular	–	1**	1	1

x No change in flow regimes.

1 Easy transition.

2 Transition influenced by capillary forces.

– Transition not possible without going through other flow regimes.

* Modified single phase flow for non-wetting flow because of a film of wetting fluid at the pore walls.

** Possible only for non-wetting phase displacing the wetting phase.

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APPENDIX B

MEYER'S METHOD

The radius r of a pore is defined to be equal to the radius of a capillary tube which will just allow mercury to enter it against capillary force at the same pressure as that at which the pore will fill, if connected to a mercury source.

Let $\nu(r)$ be the fraction (volumetric) of the total void space occupied by r-pores i.e. pores whose radii lie in the range r to r+dr. The number of such r pores in a unit volume will be given by

$$a(r)\ dr = \frac{f\,\nu(r)}{Kr^3} \qquad \text{(B.1)}$$

where f = fractional porosity

Kr^3 = vol. of a single pore of radius r

It is necessary to designate one representative point in the interior of each pore which we shall term "centre of the pore". For our purpose, any point will do so long as it is not too close to the wall of the pore and is consistently chosen, e.g. c.g. of the void space will serve. Also, we define a volume dv so small that the probability of the centres of two or more r-pores being located in this volume may be neglected.

Let the probability of m r-pores being located in any volume v be $\psi_m(v,r)dr$. Then for randomly distributed pores

$$\psi_m(v+dv,r)\,dr = \psi_m(v,r)dr\left[1-(adr)\,dv\right] + \psi_{m-1}(v,r)dr\,(adr)dv \qquad (B.2)$$

which on re-arranging gives

$$\frac{d(\psi_m\,dr)}{dv} = \frac{\left[(a\,dr)v\right]^m}{m!}\exp\left[-(adr)\,v\right] \qquad (B.3)$$

Now we define a volume $v(r_o,r)$ such that, if an r-pore is located in $v(r_o,r)$, it may be expected to be connected to an r_o-pore. This can be done if we assume that two pores are connected if the centre of the smaller lies in a volume adjacent to the larger pore, which is the difference between the volume of a pore whose radius equals the sum of the radii of the two pores minus the volume of the larger pore i.e. for $r_o > r$

$$v(r_o,r) = K(r_o+r)^3 - Kr_o^3 = K(3r^2\,r_o + 3r\,r_o^2 + r^3) \qquad (B.4)$$

Now if in Eq.(B-3) v is replaced by $v(r_o,r)$, we get the probability of m r-pores all being joined to the same r_o-pore. The probable number of such groups of pores which would exist in a unit volume would be given by the product of this probability times the number of $v\,(r_o,r)$ volumes in a unit cube (which is equal to the number of r_o pores in a unit cube). This number is equal to

$$a(r_o)dr\,\psi_m\,(v(r_o,r),r)\,dr$$

or $$a(r_o)dr\,\psi_m\,(r_o,r)\,dr$$

We are here interested in $\psi_o(r_o, r)dr$ which is the probability of an r_o pore not being connected to an r-pore.

Let a porous rock be subjected to mercury pressure such that all pores of radius $\geq r$ would fill if they had access to mercury, and let $\Gamma(r)$ be the measured fraction of the pore volume that is filled up with injected mercury at that pressure. Let $\theta(r)$ be the actual fraction of the pore-volume devoted to pores of radius $\geq r$.

If the simplifying assumption is made that only pores of radius $\geq r$ which will fail to fill are those that are not connected to any other pores of equal or larger radius. That is the probability of an r_o pore failing to fill is given by the multiplicative law of probability $\int_r^{\infty} \psi_o (r_o, r)dr$.

The total number of pores of radius $\geq r_o$ which will fail to fill is given by the expression

$$\Psi(r_o, r) = \int_{r_o}^{\infty} a(r)dr \left\{ \int_r^{\infty} \Pi \psi_o(r_o, r)\, dr \right\} \qquad (B.5)$$

Hence $$\Gamma(r) = \theta(r) \left[1 - \frac{\Psi(r_o, r)}{\int_{r_o}^{\infty} a(r)dr} \right] \qquad (B.6)$$

This is the expression from which we shall obtain true pore-size distribution $\theta(r)$ from the actual distribution $\Gamma(r)$.

Numerical Approximation:

Since the above expression is not convenient for numerical calculation the following approximation are used. The radius r

is discritized so that it takes only a finite number of values $r_n < r_{n-1} < \cdots < r_1$ and

$$\Delta r_i = r_{i-1} - r_i \qquad i = 1,2 \cdots$$

$$a_i = \int_{r_i}^{r_{i-1}} a(r)dr$$

$$\gamma_i = \Gamma(r_i) - \Gamma(r_{i-1})$$

$$\nu_i = \theta(r_i) - \theta(r_{i-1})$$

$$\psi_{ij} = \exp\left[-a_i\, v(r_i, r_j)\right]$$

$$\Psi(r_i, r_j) = \sum_{k=1}^{i} a_k \prod_{l=1}^{j} \psi_{kl}$$

Substituting these expressions inEq.(B.6) gives the approximate equation

$$\Gamma(r_i) = \sum_{k=1}^{i} \gamma_k = \sum_{k=1}^{i} \nu_k \times \left[1 - \frac{\sum_{k=1}^{i} a_k \prod_{l=1}^{j} \psi_{kl}}{\sum_{k=1}^{i} a_k}\right] \qquad (B.6a)$$

Algorithm:

(1) Assume a value of ν_i and calculate a_i and ψ_{ij}.

(2) Using these values solve Eq. (B.6a) for ν_i.

(3) If computed ν_i value is not close enough to the assumed value, make another assumption and repeat this process.

***

APPENDIX C

GLOSSARY OF TERMS USED

Porosity (f) is the ratio between the void space and bulk volume in a porous medium.

Capillary Pressure (P_c) is the difference in pressures across a fluid/fluid interface. Capillary pressure curve describes the changes in capillary (threshold) pressure of a porous as a function of its fluid saturation.

Threshold Pressure (P_T) is the minimum excess pressure must be maintained in the non-wetting phase to enable it enter a given porous medium.

Saturation(S) of any fluid in a porous medium is the ratio between the volume of the fluid in the medium to its pore volume.

Contact Angle (Θ) is the angle (through the displacing phase) that the fluid/fluid interface makes with the surface of the porous medium.

Wetting Phase is the fluid in a porous medium whose contact angle with the solid surface is less than 90°. If the contact angle is more than 90° it is called non-wetting phase.

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APPENDIX D

PROGRAM LISTING OF MEYER'S METHOD

N	Number of data in the set
SIGMA	Interfacial tension
THETA	Contact angle of non-wetting phase
POR	Porosity
R(I)	Pore-size corresponding to P(I)
PC	Capillary pressure
SGAMA	Cumulative Volumeof Mercury Injected.
ESTNU	Assumed value of nu
NU	Computed nu
DIFNU	Difference between estimated and computed nu
SV(I,J)	$v(r_i, r_j)$; characteristic volume
PSI(I,J)	ψ_{ij}
PSIR(I,J)	Ψ

ISN SOURCE STATEMENT

```
 $IBFTC MAIN
C       MEYERS METHOD
C        PC   IN   PSI
C       CAT=1.0 MEANS THE USUAL VALUES OF CHANGE ARE NOT TO BE USED
        COMMON/A1/PSI(20,20),TEMP(20,20),SUMA(20),SGAMA(20)
        COMMON/A2/RS(20),RC(20),SIGMA
        COMMON/A3/NU(500) ,POR
        DIMENSION P(20),SV(20,20),R(20),A(20),DIFNU(500),ESTNU(500)
        REAL NU
        READ 60,N
     60 FORMAT(I4)
        PRINT120
    120 FORMAT(1H1 )
        READ62,SIGMA,THETA
     62 FORMAT(5F10.3)
     65 FORMAT(5F10.5)
        THETA= THETA*3.1416/180.
        READ62,POR
        PRINT50,THETA
     50 FORMAT(5X,*THETA=*,F10.5)
        N=N+1
        DO12 I=2,N
        R(I)=0.0
        RS(I)=0.0
        RC(I)=0.0
        A(I)=0.0
        SUMA(I)=0.0
        DO 12 J=1,N
        SV(I,J)=0.0
        PSI(I,J)=0.0
        PSIR=0.0
     12 CONTINUE
        DO 101 IK=2,N
    101 READ65,P(IK),SGAMA(IK)
        PRINT20,(P(IK),IK=2,N),(SGAMA(IK),IK=2,N)
        DO 40 IM=2,N
     40 SGAMA(IM)=SGAMA(IM)/POR
        PRINT5
      5 FORMAT(5X,12HACTUAL VALUE ,10X,2HIK ,5X,10HTRUE VALUE  /)
        DO10 J=2,N
        CAT=0.0
        DIFNU(1)=0.0
        IK=2
        ESTNU(IK)=SGAMA(J)
      2 CALL SI(IK,PSIR,A,ESTNU,THETA,N,P,R,SV,J,J)
        IF(IK.EQ.2.AND.J.EQ.2)PRINT20,(R(I),I=1,N)
        IF(IK.EQ.2.AND.J.EQ.2)PRINT20,((SV(I,IJ),IJ=2,N),I=2,N)
     20 FORMAT(5X,8E15.8)
        NU(IK)=SGAMA(J)/(1.-PSIR/SUMA(J))
        DIFNU(IK)=NU(IK)-ESTNU(IK)
        IF(DIFNU(IK).GT.0.0.AND.DIFNU(IK-1).LT.0.0)GO TO 25
        IF(DIFNU(IK).LT.0.0.AND.DIFNU(IK-1).GT.0.0) GO TO 25
        IF(ABS(DIFNU(IK)).LE.0.0002) GO TO 7
        IF(CAT.EQ.1.0)GO TO 25
        IF(ESTNU(IK).GT.0.0001)CHANGE=0.0001
```

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CGG145                                                FORTRAN SOURCE LIST MAIN
  ISN        SOURCE STATEMENT

  133           IF(ESTNU(IK).GT.0.001)CHANGE=0.001
  136           IF(ESTNU(IK).GT.0.01)CHANGE=0.01
  141           IF(ESTNU(IK).GT.0.1)CHANGE=0.1
  144           IF(ESTNU(IK).GT.0.9)CHANGE=0.005
  147           IF(DIFNU(IK).GT.0.0) ESTNU(IK+1)=ESTNU(IK)+CHANGE
  152           IF(DIFNU(IK).LT.0.0) ESTNU(IK+1)=ESTNU(IK)-CHANGE
  155           IK=IK+1
  156           IF(IK.GE.500) GO TO 7
  161           GO TO 2
  162        25 CHANGE=CHANGE/2.
  163           IF(DIFNU(IK).GT.0.0) ESTNU(IK+1)=ESTNU(IK)+CHANGE
  166           IF(DIFNU(IK).LT.0.0) ESTNU(IK+1)=ESTNU(IK)-CHANGE
  171           IK=IK+1
  172           CAT=1.0
  173           GO TO 2
  174         7 PRINT 6,SGAMA(J),IK,ESTNU(IK)
  175         6 FORMAT(5X,F10.5,10X, I5,5X,F10.5)
  176        10 CONTINUE
  200           PRINT8,(A(J),SUMA(J),J=2,N)
  205         8 FORMAT(10X,E15.7,10X,E15.7)
  206        22 STOP
  207           END
CGG145                                                IBMAP ASSEMBLY MAIN


 NO MESSAGES FOR ABOVE ASSEMBLY
```

CGG145 FORTRAN SOURCE LIST

ISN SOURCE STATEMENT

```
$IBFTC SUB1
        SUBROUTINE VOL(P,R,THETA,IK,N,SV,M,IM)
        COMMON/A1/PSI(20,20),TEMP(20,20),SUMA(20),SGAMA(20)
        COMMON/A2/RS(20),RC(20),SIGMA
        COMMON/A3/NU(500) ,FOR
        DIMENSION P(20),SV(20,20),R(20) ,A(20),DIFNU(500)
        FACTOR=1./68947.3*10.**4
        DO 1 I=2,N
        R(I)=FACTOR*2.*SIGMA*COS(THETA)/P(I)
        R(I)=ABS(R(I))
        RS(I)=R(I)**2
      1 RC(I)=R(I)**3
        R(1)=20.0
        RS(1)=R(1)**2
        N1=N+1
        DO 6 I=2,N
        DO 6 J=2,N
        IF(R(J).GT.R(I))GO TO 7
      5 SV(I,J)=2.*R(I)*R(J)+RS(J)
        GO TO 6
      7 SV(I,J)=2.*R(I)*R(J)+RS(I)
      6 CONTINUE
        DO10 I=2,N
        DO10 J=2,N
     10 SV(I,J)=ABS(SV(I,J))
        RETURN
        END
```

CGG145 IBMAP ASSEMBLY SUB1

NO MESSAGES FOR ABOVE ASSEMBLY

```
CGG145                                          FORTRAN SOURCE LIST
  ISN        SOURCE STATEMENT

    0 $IBFTC SUB2
    1        SUBROUTINE SI(IK,PSIR,A,ESTNU,THETA,N,P,R,SV,IL,JK)
    2        COMMON/A1/PSI(20,20),TEMP(20,20),SUMA(20),SGAMA(20)
    3        COMMON/A2/RS(20),RC(20),SIGMA
    4        COMMON/A3/NU(500) ,POR
    5        DIMENSION P(20),SV(20,20),R(20),A(20),DIFNU(500) ,ESTNU(500)
    6        REAL NU
    7        CALL FLUN(99999)
   10        N1=N
   11        NU(IK)=ESTNU(IK)
   12        SUMA(1)=0.0
   13        IF(JK.EQ.2)CALLVOL(P,R,THETA,IK,N,SV,M,IM)
   16        I=IL
   17        A(I)=NU(IK)*(1./R(I)-1./R(I-1))*POR
   20        DO 12 J=2,N1
   21        B=-A(I)*SV(I,J)
   22        IF(B.GE.88.0) GO TO 1
   25        IF(B.LE.(-88.0)) GO TO 2
   30        PSI(I,J)=EXP(B)
   31        GO TO 12
   32      1 CONTINUE
   33     3  PSI(I,J)=1.0E30
   34        GO TO 12
   35      2 CONTINUE
   36      4 PSI(I,J)=0.0
   37     12 CONTINUE
   41        J=JK
   42        DO 8 K=2,IL
   43        TEMP(I,J)=0.
   44        PROD=1.
   45        DO 10 L=2,JK
   46        DELTAR=R(L-1)-R(L)
   47        PROD=PROD*PSI(K,L)
   50        IF(PROD.LE.0.1E-37)PROD=0.0
   53     10 CONTINUE
   55      8 TEMP(I,J)=TEMP(I,J)+A(K)*PROD
   57        PSIR=TEMP(I,J)
   60      9 CONTINUE
   61        SUMA(I)=SUMA(I-1)+A(I)
   62      5 FORMAT(5X,8E15.7)
   63        RETURN
   64        END
CGG145                                          IBMAP ASSEMBLY SUB2

  NO MESSAGES FOR ABOVE ASSEMBLY
CGG145                                          IBLDR -- JOB   000000

      *** OBJECT PROGRAM IS BEING ENTERED INTO STORAGE AT  16 HRS.  21 MTS.
```

APPENDIX E

PROGRAM LISTING NETWORK MODEL

The first subscript in each variable in the program refers to the node point.

X(1) to X(8)	The radii of the 8 tubes	
X(9) to X(16)	Length of the tubes	
X(17) to X(24)	Fluid content and flow regimes in the tubes	
	1.0	wetting (one phase flow)
	2.0	non-wetting (one phase flow)
	3.0	Displacement (non-wetting close to the node point)
	3.5	Displacement (wetting closer to the node point)
	4.1	Annular flow (displaced phase wetting)
	4.2	Annular flow (displacing phase wetting)
	4.5	Slug flow
X(25) to X(32)	Flow or no flow situation	
	1.0	Flow occurring
	2.0	Flow blocked
	1.5	Flow provisionally blocked
	2.5	Flow permanently blocked
X(33) to X(40)	Flow conductivities of the tubes to displaced fluid	
X(41) to X(48)	Flow conductivities of the tubes to displacing fluid	
X(49) to X(56)	Volume of the tubes	
X(57) to X(64)	Displaced fluid content of the tube	

X(65) to X(72)	Effective pressure drops across the tubes
X(73)	Incoming fluids 1.0 displaced 2.0 displacing 3.0 Both 4.0 none (node point isolated)
X(74)	Absolute pressure at node points
X(75) to X(82)	Appropriate conductivities of the tubes
X(83)	Volume of incoming displaced fluid
X(84)	Volume of incoming displacing fluid
X(85) to X(92)	Effective capillary pressures
X(93)	Provisional total outflow of displaced fluid
X(94)	Provisional total outflow of displacing fluid
X(95) to X(102)	Provisional inflow of displaced fluid in tubes
X(103) to X(110)	Provisional inflow of displacing fluid in tubes
X(111) to X(118)	Provisional outflow of displaced fluid from tubes
X(119) to X(126)	Provisional outflow of displacing fluid from tubes
IR	No. of rows in network
JR	No. of column in network
GAMA	Interfacial tension
THETA	Contact angle
RAD	Tube radius

COM	Cumulative distribution
GRID	Grid size
TRAP	Value of trapping factor
HYST	Hysteresis in contact angle (=0)
TIME	Time step
ISTAR-IFIN	No. of time steps for each pressure
AV	Displaced fluid content of the network
ICP	No. of pressure steps

```
$IBFTC CALC                                                                BPP0..2
      COMMON/SYMARG/X(5 ,16 ),AP(50,8),GC,VO,VW,TIME,VOF(5 ,8),IJ,IR,JR,BPP0..3
     1XA     ,EP(  ,  ),HYST,CAT,GAMMA,J,FLO(5 ,8),GRID                    BPP00040
      COMMON/PRESS/NN,A(50,50),AB(50)                                      BPP00050
      COMMON/SOL/AA(5 ,5 ),BB(50),AV(40),WR(40),WO(40),WI(40),DEN(4 )      BPP0..6.
      COMMON/SOLB/CAP(1 ,10),I,ICHANG,ARAT,TRAP                            BPP0..7.
      COMMON/CHAN/DIFO,WDIF                                                BPP00080
      COMMON/CHIN/ICAN(50,8),AWDIF(50,8),ADIFO(50,8),BASE                  BPP00090
      COMMON/SOLC/AOO,CP,JIM,ICP                                           BPP0.1.
      COMMON/SIM/COM(15),RAD(15),KL,LK                                     BPP0.11.
C     READ AND PRINT ALL THE RELEVANT INPUT DATA                           BPP00120
      CALL FLUN(99999)                                                     BPP0.12.
      DO 9   IKJ=1,2                                                       BPP0.12.
      READ 1  ,IR,JR,GAMMA,THETA,CP,VO,VW                                  BPP0.13.
      PRINT987                                                             BPP0013.
  987 FORMAT(1H1 )                                                         BPP0.13.
      PRINT 1 ,IR,JR,GAMMA,THETA,CP,VO,VW                                  BPP00140
      READ 30,KL,LK                                                        BPP00150
      PRINT 30,IR,JR,KL,LK                                                 BPP0016.
      READ 4 ,(COM(I),I=1,LK)                                              BPP0.17.
      PRINT 4 ,(COM(I),I=1,LK)                                             BPP00180
      READ 40,(RAD(J),J=1,LK)                                              BPP00190
      PRINT 4 ,(RAD(J),J=1,LK)                                             BPP0.2..
      PRINT 4 ,VO,VW,CP                                                    BPP0.21.
      READ 40,GRID                                                         BPP00220
      PRINT 40,GRID                                                        BPP00230
      READ 12,XA,HYST,TRAP                                                 BPP00240
      PRINT 12,XA,HYST,TRAP                                                BPP00250
      READ 7,TIME                                                          BPP00260
      PRINT 7,TIME                                                         BPP00270
      READ 10,ISTAR,IFIN                                                   BPP00280
      PRINT 10,ISTAR,IFIN                                                  BPP00290
      I=ISTAR-1                                                            BPP00300
      READ 37,WR(I+1),DEN(I+1),STW,STO                                     BPP00310
      IF(ISTAR.EQ.1)I=1                                                    BPP00320
      READ 37,AV(1),WO(1), WO(I),WI(I)                                     BPP00330
      AOO=WO(I)                                                            BPP00340
    7 FORMAT(1X,F15.10)                                                    BPP00350
   10 FORMAT(2I3,6F10.5)                                                   BPP00360
   11 FORMAT(20X,4I4)                                                      BPP00370
   12 FORMAT(8F10.5)                                                       BPP00380
   13 FORMAT(6F10.5)                                                       BPP00390
   14 FORMAT(12F10.5)                                                      BPP00400
   40 FORMAT(1X,8F10.5)                                                    BPP00410
   30 FORMAT(1X,2I8)                                                       BPP00420
   37 FORMAT(4X,8E12.5)                                                    BPP00430
   50 FORMAT(20X,15HOIL SATURATION=,F10.4,17HWATER SATURATION=,F10.4)      BPP00440
   51 FORMAT(20X,7HTHE PT.,I4,25HIS BETWEEN 1AND 4 IN C73    )             BPP00450
   52 FORMAT(20X,7HTHE PT.,I4,12HHAS 4 IN C73  )                           BPP00460
  100 FORMAT(//// 8(9X,1H ))                                               BPP00470
  111 FORMAT(30X,21HPRESSURE DISTRIBUTION   )                              BPP00480
  117 FORMAT(//1X,30X,18HFLUID DISTRIBUTION   )                            BPP00490
  310 FORMAT(//20X,I4,7F13.5//)                                            BPP00500
  759 FORMAT(20X,*CONTACT ANGLE=* F6.2,*DEGREES*)                          BPP0.51.
  760 FORMAT(20X,*VISCOSITY RATIO(OIL/WATER)=*,F6.2)                       BPP0.52.
```

```
   SOURCE STATEMENT

751 FORMAT(1H1)
    N=IR*JR
    JIM=N-JR
C   THETA IS CONTACT ANGLE AND GAMMA IS INTERFACIAL TENSION
    ARAT=VO/VW
    ARG=THETA*3.1416/180.
    GC=1.782*GAMMA*COS(ARG)/68947.31
    CAT=0.0
    PRINT 759,THETA
C   READ DATA FROM TAPE
    CALL SIMU
    PRINT37,((X(J,K),K=1,8),J=1,N)
    PRINT37,((X(J,K),K=57,64),J=1,N)
    DO 20 IJ=1,N
    IK=IJ/JR+1
    JK=IJ-JR*(IK-1)
    IF(JK.LE.0)IK=IK-1
    IF(JK.LE.0)JK=JR
    EP(IK,JK)=X(IJ,74)
    CAP(IK,JK)=0.0
    DO 39 IA=1,8
    X(IJ,IA+16)=1.0
    X(IJ,IA+24)=1.0
    X(IJ,IA+136)=THETA
    IF(X(IJ,IA).EQ.0.0)X(IJ,IA+24)=2.0
    X(IJ,IA+40)=X(IJ,IA+32)*VO/VW
    X(IJ,IA+56)=X(IJ,IA+48)
    X(IJ,IA+74)=X(IJ,IA+32)
    X(IJ,IA+84)=0.0
    X(IJ,IA+94)=0.0
    X(IJ,IA+102)=0.0
    X(IJ,IA+110)=0.0
    X(IJ,IA+118)=0.0
 39 CONTINUE
    X(IJ,83)=0.0
    X(IJ,84)=0.0
    X(IJ,93)=0.0
    X(IJ,73)=1.0
    X(IJ,94)=0.0
 20 CONTINUE
    PRINT 12,GAMMA
    STW=0.0
    STO=0.0
    AV(1)=0.0
    DO 900 ICP=1,12
    WI(1)=0.0
    DO 900 ICP=1,10
    IF(ICP.GE.3)TIME=0.001
    IF(ICP.GE.5)TIME=0.005
    IF(ICP.GE.8)TIME=0.01
    READ7,CP
    PRINT7, CP
    DO 700 I=ISTAR,IFIN
    IF(ICP.EQ.1)  WO(1)=0.0
    IF(ICP.EQ.1)WI(1)=0.0
```

FORTRAN SOURCE LIST CALC

SOURCE STATEMENT

```
 48 CONTINUE
C     FRAME EXAMINE AND SOLVE THE SYSTEM OF EQUATIONS
      CALL SOLVE
      IF(ICP.LT.10) GO TO 107
108   PRINT 111
C     PRINT PRESS DISTRIBUTION
      DO 107 IB=1,IR
      PRINT 100
      PRINT 14,(EP(IB,JK),JK=1,JR)
107   CONTINUE
      PRINT 117
      AOO=0.0
      AWO=0.0
      SWL=0.0
      IF(I.NE.1)SWL=1.0-AV(I)/AV(1)
      AV(I)=0.0
      ILK=0
      SATL=0.0
      SATO=0.0
      DO 300 KRS=1,N
C     CALL POINTS IN PROPER SEQUENCE
      IF(KRS.LE.ILK) GO TO 300
      DO 305 K=KRS,N
      IK=K/JR+1
      JK=K-JR*(IK-1)
      IF(JK.LE.0)IK=IK-1
      IF(JK.LE.0)JK=JR
      IF(JK.EQ.JR)GO TO 320
      DPE=EP(IK,JK)-EP(IK,JK+1)+CAP(IK,JK)
      IF(DPE.GE.0.0)GO TO 320
305   CONTINUE
320   ILK=K
      MK=ILK-KRS+1
      DO 350 KR=1,MK
      IJ=ILK-KR+1
      J=IJ
      IF(ICP.LT.15)GO TO 2
      PRINT 10,IJ
  2   CONTINUE
      IK=IJ/JR+1
      JK=IJ-JR*(IK-1)
      IF(JK.LE.0) IK=IK-1
      IF(JK.LE.0)JK=JR
      IJA=IJ
      M=1
      VWI=0.0
      VOI=0.0
      MMK=0
      BASE=0.0
      IF(X(J,73).EQ.4.0) GO TO 291
C     COMPUTE FLOW RATES FOR OIL AND WATER INCOMING OUTGOING
      CALL FLOW
      VOI=X(J,83)
      VWI=X(J,84)
      IF(IK.EQ.1)VOI=0.0
```

SOURCE STATEMENT

```
      IF(IK.EQ.1)VWI=0.0                                                BPP01560
      IF(IK.EQ.1)GO TO 214                                              BPP01570
C     UPDATE X(73)=LIQUIDS ENTERING THE JUNCTION POINT                  BPP01580
      IF(VOI.EQ.0.0.AND.VWI.EQ.0.0)X(J,73)= 4.0                         BPP01590
      IF(VOI.EQ.0.0.AND.VWI.NE.0.0)X(J,73)=2.0                          BPP01600
      IF(VOI.NE.0.0.AND.VWI.NE.0.0)X(J,73)=3.0                          BPP01610
      IF(VOI.NE.0.0.AND.VWI.EQ.0.0)X(J,73)=1.0                          BPP01620
      VOI=ABS(VOI)                                                      BPP01621
      VWI=ABS(VWI)                                                      BPP01622
      IF(IJ.GT.J1M)GO TO 290                                            BPP01630
C     COMPUTE OUT FLOWING VOLUMES                                       BPP01640
  214 VOO=X(J,93)                                                       BPP01650
      VWO=X(J,94)                                                       BPP01660
      VOO=ABS(VOO)                                                      BPP01670
      VWO=ABS(VWO)                                                      BPP01680
      DELTA=VOI+VWI-VOO-VWO                                             BPP01690
      IF(VOO.LE.0.10E-10)VOO=0.0                                        BPP01700
      IF(VWO.LE.0.10E-10)VWO=0.0                                        BPP01710
      IF(VWI.LE.0.10E-10)VWI=0.0                                        BPP01720
      IF(VOI.LE.0.10E-10)VOI=0.0                                        BPP01730
      IF(ABS(DELTA).LE.0.1E-10) DELTA=0.0                               BPP01740
      DELO=VOI-VOO                                                      BPP01750
      DELOW=VWI-VWO                                                     BPP01760
      DELO=ABS(DELO)                                                    BPP01770
      DELOW=ABS(DELOW)                                                  BPP01780
      IF(DELO.LT.0.1E-10)VOO=VOI                                        BPP01790
      IF(DELOW.LT.0.1E-10) VWO=VWI                                      BPP01800
      IF(ICP.LT.15)GO TO 1                                              BPP01801
  888 PRINT37,VOI,VOO,VWI,VWO,DELTA                                     BPP01810
      IF(DELTA.NE.0.0)PRINT37,(X(J,KA),KA=75,82)                        BPP01820
      IF(DELTA.NE.0.0)PRINT37,(X(J,KA),KA=65,72)                        BPP01830
      IF(DELTA.NE.0.0)PRINT37,(X(J,KA+94),KA=1,32)                      BPP01840
      IF(DELTA.EQ.0.)PRINT37,(X(J,KA),KA=75,82)                         BPP01841
      IF(DELTA.EQ.0.)PRINT37,(X(J,KA),KA=65,72)                         BPP01842
    1 CONTINUE                                                          BPP01850
C     UPDATE OIL CONTENT OF TUBES                                       BPP01851
      DO 21 K=1,8                                                       BPP01852
      DEN(K)=X(J,K+56)                                                  BPP01856
   21 X(J,K+56)=VOF(J,K)                                                BPP01857
      DO 470 JP=1,8                                                     BPP01860
      ICAN(J,JP)=0                                                      BPP01870
      AWDIF(J,JP)=0.0                                                   BPP01880
      ADIFO(J,JP)=0.0                                                   BPP01890
      IF(X(J,JP+16).EQ.0.0)PRINT 11,IJ,JP                               BPP01900
  470 CONTINUE                                                          BPP01910
      CASE=0.0                                                          BPP01920
      IF(IK.NE.1.AND.VOO.EQ.0.0.AND.VWO.EQ.0.0)X(J,73)=4.0              BPP01930
      IF(IK.EQ.1.AND.VOO.EQ.0.0.AND.VOI.EQ.0.0.AND.VWO.EQ.0.0.AND.VWI.  BPP01940
     1EQ.0.0)X(J,73)=4.0                                                BPP01950
      IF (X(J,73).EQ.4.0) CASE=1.0                                      BPP01960
      IF(X(J,73).EQ.4.0) GO TO 270                                      BPP01970
C     COMPENSATE FOR IMBA ANCE IM INFLOW-OUTFLOW AT A POINT BYPICKING TUBPP01980
C     MONTE CARLO TECHNIQUE                                             BPP01990
      IF(IJ.LE.JR) CASE=1.0                                             BPP02000
      IF(IJ.LE.JR) GO TO 4805                                           BPP02010
```

SOURCE STATEMENT

```
      IF(VOI.GE.VOO.AND.VWI.GE.VWO)CASE=1.0
      IF(VOI.GE.VOO.AND.VWI.GE.VWO) GO TO 4805
      IF((VOI+VWI).LE.0.0) GO TO 4805
      WDIF=VWI-VWO-(DELTA*VWI)/(VOI+VWI)
      DIFO=VOI-VOO-(DELTA*VOI)/(VOI+VWI)
      IF(WDIF.LE.0.1E-10)WDIF=0.0
      IF(DIFO.LE.0.1E-10)DIFO=0.0
      IF(DIFO.LE.0.0.AND.WDIF.LE.0.0)GO TO 4805
      CALL CHANGE
      IF(DIFO.NE.0.0.OR.WDIF.NE.0.0)PRINT37,(X(J,KA+74),KA=1,8)
C     BASE.EQ.1.0 MEANS UPSTREAM DATA HAS TO BE CORRECTED DUE TO FLOW CH
 4805 DO 1005 K=1,8
      X(J,K+56)=DEN(K)
      X(J,K+16)=FLO(J,K)
      IF(X(J,K+24).GE.1.5)GO TO 1005
      IF(X(J,K+64).LE.0.0)GO TO 1005
      X(J,K+110)=X(J,K+94)+X(J,K+56)-VOF(J,K)
      X(J,K+118)=X(J,K+102)+VOF(J,K)-X(J,K+56)
      X(J,K+56)=VOF(J,K)
 1005 CONTINUE
  270 CAT=1.0
      CALL COND(1)
      CAT=0.0
      IF(MMK.EQ.0.AND.BASE.EQ.0.0) GO TO 291
      IF(BASE.EQ.1.0) GO TO 479
      ICAN(J,M)=0
      GO TO 483
  479 DO 481 ICA=6,8
      IF(BASE.EQ.1.0)PRINT 11,IJ,ICAN(J,1),ICAN(J,7),ICAN(J,8)
      IF(BASE.EQ.1.0)BASE=2.0
      M=ICA
      IF(ICA.EQ.6)M=1
      MMK=ICAN(J,M)
      ICAN(J,M)=0
      IF(MMK.EQ.0) GO TO 482
      WDIF=AWDIF(J,M)
      DIFO=ADIFO(J,M)
      IF(X(J,M+64).GT.0.0)CASE=2.0
      IF(CASE.LT.2.0)J=MMK
      IF(WDIF.LE.0.0.AND.DIFO.LE.0.0) GO TO 482
      DO 478 K=1,8
      FLO(J,K)=X(J,K+16)
      VOF(J,K)=X(J,K+56)
      AP(J,K)=0.0
      IF(X(J,K+64).GT.0.0)AP(J,K)=X(J,K+64)
  478 CONTINUE
  430 IF(WDIF.LE.0.1E-10)WDIF=0.0
      IF(DIFO.LE.0.1E-10)DIFO=0.0
      IF(DIFO.LE.0.0.AND.WDIF.LE.0.0) GO TO 485
      CALL CHANGE
C     ENTER CHANGES IN VOL OUTFLOW/INFLOW,AND FLUID CONTENT
  485 CONTINUE
  486 DO 105 K=1,8
      X(J,K+56)=DEN(K)
      X(J,K+16)=FLO(J,K)
```

SOURCE STATEMENT

```
      IF(X(J,K+24).GE.1.5)GO TO 105
      IF(X(J,K+64).LE.0.0)GO TO 105
      X(J,K+110)=X(J,K+94)+X(J,K+56)-VOF(J,K)
      X(J,K+118)=X(J,K+102)+VOF(J,K)-X(J,K+56)
      X(J,K+56)=VOF(J,K)
  105 CONTINUE
      CAT=1.0
      CALL COND(I)
      CAT=0.0
      IF(MMK.EQ.0.AND.BASE.EQ.0.0) GO TO 291
      IF(BASE.EQ.1.0) GO TO 479
      ICAN(J,M)=0
  482 CONTINUE
  481 CONTINUE
  483 BASE=0.0
      MMK=0
      J=IJA
  291 IB=IJ+JR
      DO 330 K=6,9
      IA=K
      IF(K.EQ.9) IA=1
      AV(I)=AV(I)+X(J,IA+56)
      IF(X(J,IA+56).LT.0.0.OR.X(J,IA+56).GT.X(J,IA+48))PRINT10,J,IA
      IF(X(J,IA+56).LT.0.0.OR.X(J,IA+56).GT.X(J,IA+48))PRINT37,X(J,IA+48
     1),X(J,IA+56)
  330 CONTINUE
      IF(I.EQ.1.AND.ICP.EQ.1)VOLPOR=AV(1)
C     COMPUTE TOTAL OUTFLOW OF FLUIDS FROM THE SAMPLE
      IF(VOI.LE.0.10E-10)VOI=0.0
      IF(VWI.LE.0.10E-10)VWI=0.0
      IF(IB.LE.N) GO TO 292
      IF(ICP.LT.15)GO TO 3
      PRINT 37,VOI,VWI
    3 CONTINUE
      AOO=AOO+VOI
      AWO=AWO+VWI
      DO 290 IA=7,9
      K=IA
      IF(K.EQ.9) K=1
      SATL=SATL+X(J,K+56)
      SATO=SATO+X(J,K+48)
  290 CONTINUE
  292 CONTINUE
C     PRINT FLOW DISTRIBUTION
      IF(ICP.LT.15)GO TO 4
      PRINT37,(X(J,KA),KA=57,64)
  777 PRINT12,(X(J,K),K=17,32)
      IF(X(J,73).EQ.4.0) PRINT52,IJ
    4 CONTINUE
      IF(I.EQ.1.AND.ICP.EQ.1)GO TO 2222
      GO TO 79
 2222 CONTINUE
      IF(IK.NE.1)GO TO 213
      X(J,73)=2.
      DO 212 K=3,5
```

```
N        SOURCE STATEMENT

         IF(X(J,K+16).EQ.1.0) X(J,K+16)=3.0
     212 CONTINUE
     213 IF(IK.NE.2) GO TO 79
         DO 218 IA=7,9
         K=IA
         IF(K.EQ.9) K=1
         IF(X(J,K+16).EQ.1.0) X(J,K+16)=3.5
     218 CONTINUE
      79 CONTINUE
         X(J,83)=0.0
         X(J,84)=0.0
         X(J,93)=0.0
         X(J,94)=0.0
         VOI=0.0
         VWI=0.0
     296 CONTINUE
     350 CONTINUE
     300 CONTINUE
         PRINT37,AV(I)
         SO=AV(I)/VOLPOR
         SW=1.0-SO
         PRINT 50,SO,SW
     690 CONTINUE
         WI(I)=AWO
         WI(1)=WO(1)*ARAT
         CUML=(STO+STW)/AV(1)
         WO(I)=AOO
         STW=STW+WI(I)
         STO=STO+WO(I)
         PRINT 37, WO(1),WO(I),STO,STW,WI(I)
         W=WO(1)*0.01
         IF(I.GT.2.AND.AOO.LE.W) GO TO 800
     700 CONTINUE
     800 CONTINUE
     900 CONTINUE
   C     CALCULATE AND PRINT POROSITY AND PERMEABILITY
         AJR=JR
         AIR=IR
         POR=AV(1)/((AJR-1.)*(AIR-1.)*GRID**3)
         PERM=WI(1)*VW*(AIR-1.)/(TIME*GRID*(AJR-1.)*CP)
         PRINT 12, POR,PERM
         STOP
         END
```

IBMAP ASSEMBLY CALC 12/04/

```
ROR MESSAGES

T 307          ERROR 1311   ISN-221   DO VARIABLE REDEFINED IN ITS OWN RANGE.

VERITY WAS 0.
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      SOURCE STATEMENT

      CALL PDIF
C     AVOID INFLOW FROM OUTLET END OR FROM INLET END .TRAP APPROPRIATE T
C     UBES
      K=IJ
      DO 76 KL=2,5
      IF(K.GT.JIM) GO TO 76
      COL=0.0
      IJK=IJ
      IF(X(IJK,KL+24).GE. 1.5) GO TO 76
      AS=0.0
      IF(K.GT.NN.AND.K.LE.JIM) AS=1.0
      IF(AS.EQ.1.0.AND.X(IJK,KL+64).LT.0.0) AS=2. 0
      IF(AS.EQ.2.0.AND.KL.GE.3.AND.KL.LE.5)COL=0.5
      IF(K.LE.JR.AND.X(IJK,KL+64).LT.0.0) COL=0.5
      IF(X(IJK,KL+16).LE.2.0) GO TO 55
      IF(X(IJK,KL+16).GT.4.0)GO TO 55
      IF(K.LE.JR) GO TO 55
      DP=0.0
      DP=X(IJK,KL+84)
      DP=DP*(1.+TRAP)
      ADP=X(IJK,KL+64)-X(IJK,KL+84)
      IF(DP.LE.0.0.AND.ADP.LE.0.0) GO TO 55
      IF(ADP.GE.0.0.AND.DP.GE.0.0) GO TO 55
      DP=ABS(DP)
      ADP=ABS(ADP)
      IF(ADP.LT.DP) COL=0.5
   55 IF(COL.EQ.0.5) X(IJK,KL+24)=1.5
      IF(COL.EQ.0.5) CO=0.5
   76 CONTINUE
      IF(CO.EQ.0.0) GO TO 77
      CAT=0.0
      COUNT=COUNT+1
      J=IJ
      CALL COND(1)
   77 CONTINUE
   87 CONTINUE
      DO 82 IL=1,8
      IF(X(IJ ,73).EQ.4.0) GO TO 82
      IF(X(IJ,IL+24).GE.1.5) GO TO 82
      CPA=X(IJ,IL+84)
      CPT=CPT+X(IJ,IL+74)*CPA
      VS=VS+X(IJ,IL+74)
      IF(IL.EQ.2) CAP(IK,JK)=CPA
   82 CONTINUE
      IF(VS.EQ.0.0) GO TO 85
      IF(IJ.LT.IS.OR.IJ.GT.IT) GO TO 85
      VA=0.0
      DO 70 K=1,8
      X(IJ,K+94)=0.0
      X(IJ,K+102)=0.0
      X(IJ,K+110)=0.0
      X(IJ,K+118)=0.0
      IA=IK
      JA=JK
      IF(K.EQ.1) IA=IK-1
```

FORTRAN SOURCE LIST UB 1 12/04/

```
N       SOURCE STATEMENT

        IF(K.LE.3) JA=JK+1                                                BPP04540
        IF(K.GE.5.AND.K.LE.7) JA=JK-1                                     BPP04550
        IF(K.GE.3.AND.K.LE.5)IA=IK+1                                      BPP04560
        IF(K.GE.7) IA=IK-1                                                BPP04570
        IJC=(IA-1)*JR+JA                                                  BPP04580
        AA(IJ,IJC)=-X(IJ,K+74)                                            BPP04590
        IF(IJC.LE.JR) VA=VA+AA(IJ,IJC)*CP                                 BPP04600
     70 CONTINUE                                                          BPP04610
        BB(IJ)=-VA-CPT                                                    BPP04620
     85 AA(IJ,IJ)=VS                                                      BPP04630
     86 CONTINUE                                                          BPP04640
        IF(IC.NE.1.AND.COUNT.EQ.0) GO TO 78                               BPP04650
        DO 66 IN=1,NN                                                     BPP04660
        INR=IN+JR                                                         BPP04670
        AB(IN)=BB(INR)                                                    BPP04680
        DO 66 JN=1,NN                                                     BPP04690
        JNR=JN+JR                                                         BPP04700
        A(IN,JN)=AA(INR,JNR)                                              BPP04710
     66 CONTINUE                                                          BPP04720
        CALL PRSOL(1)                                                     BPP04730
        CALL PRSOL(2)                                                     BPP04740
        DO 75 K=1,N                                                       BPP04750
        BB(K)=CP                                                          BPP04760
        IF(K.GT.JIM) BB(K)=0.                                             BPP04770
        IF(K.LE.JR.OR.K.GT.JIM) GO TO 73                                  BPP04780
        KK=K-JR                                                           BPP04790
        BB(K)=AB(KK)                                                      BPP04800
     73 IK=K/JR+1                                                         BPP04810
        JK=K-JR*(IK-1)                                                    BPP04820
        IF(JK.EQ.0) IK=IK-1                                               BPP04830
        IF(JK.EQ.0) JK=JR                                                 BPP04840
        EP(IK,JK)=BB(K)                                                   BPP04850
     75 CONTINUE                                                          BPP04860
     78 CONTINUE                                                          BPP04870
        PRINT 10,COUNT                                                    BPP04880
        IF(COUNT.NE.0) GO TO 80                                           BPP04890
        IF(IC.EQ.1) GO TO 80                                              BPP04900
        RETURN                                                            BPP04910
        END                                                               BPP04920
```

IBMAP ASSEMBLY UB 1 12/04/

ESSAGES FOR ABOVE ASSEMBLY

N SOURCE STATEMENT

```
$IBFTC SUB
       SUBROUTINE PRSOL(KKK)
       COMMON/PRESS/NN,A(50,50),AB(50)
       GO TO (1000,2000),KKK
C      REDUCE MATRIX BY GAUSS ELIMINATION PROCEDURE
 1000  N=NN+1
       DO 230 I=1,NN
       A(I,N)=-AB(I)
  230  CONTINUE
       DO 282 L=1,NN
       M=L+1
       IF(M.GT.NN) GO TO 282
       DO 281 I=M,NN
       IF(A(L,L).EQ.0.0) GO TO 281
       C=A(I,L)/A(L,L)
       IF(C.EQ.0.0) GO TO 281
       DO 280 J=1,N
       IF(A(L,J).EQ.0.0) GO TO 280
       Z=C*A(L,J)
       A(I,J)=A(I,J)-Z
  280  CONTINUE
  281  CONTINUE
  282  CONTINUE
       DO 340 L=1,NN
       I=N-L
       C=A(I,I)
       DO 320 J=1,N
       IF(C.EQ.0.0) GO TO 320
       IF(A(I,J).EQ.0.0) GO TO 320
       A(I,J)=A(I,J)/C
  320  CONTINUE
       BA=A(I,N)
       IA=I-1
       IF(IA.EQ.0) GO TO 340
       IF(BA.EQ.0.0) GO TO 340
       DO 330 IB=1,IA
       A(IB,N)=A(IB,N)-BA*A(IB,I)
  330  A(IB,I)=0.0
  340  CONTINUE
       GO TO 500
 2000  DO 450 I=1,NN
  450  AB(I)=-A(I,N)
  500  RETURN
       END
```

IBMAP ASSEMBLY UB 2 12/04/

ESSAGES FOR ABOVE ASSEMBLY

SOURCE STATEMENT

```
$IBFTCSUB 3
      SUBROUTINE FLOW
      COMMON/SYMARG/X(50,160),AP(50,8),GC,VO,VW,TIME,VOF(50,8),IJ,IR,JR,
     1XA     ,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID
C     FLOW CAPICITY OF TUBES
      ARAT=VO/VW
      N=IR*JR
      IB=N-2*JR
      X(J,93)=0.
      X(J,94)=0.0
      DO 200 K=1,8
      VOF(J,K)=X(J,K+56)
      AP(J,K)=0.
      IF(X(J,K+64).GT.0.0)AP(J,K)=X(J,K+64)
      X(J,K+94)=0.0
      X(J,K+102)=0.0
      X(J,K+110)=0.0
      X(J,K+118)=0.0
      IF(X(J,73).EQ.4.0) GO TO 200
C     CASE 2.0 MEANS BACK FLOW
      CASE=0.0
      FLO(J,K)=X(J,K+16)
      IF(K.GE.3.AND.K.LE.5)CASE=1.0
      IF(CASE.EQ.1.0.AND.AP(J,K).EQ.0.0) CASE=2.0
      IF(CASE.EQ.2.0)AP(J,K)=X(J,K+64)
      IF(X(J,K+24).GE.2.0)GO TO 200
      VA=AP(J,K)*X(J,K+74)
      VA=VA*TIME
      VA=ABS(VA)
      IF(VA.EQ.0.0)GO TO 200
      IF(CASE.EQ.2.0) GO TO 5
      GO TO 7
    5 IF(X(J,K+16).EQ.4.2) FLO(J,K)=4.2
      IF(X(J,K+16).EQ.4.1) FLO(J,K)=4.1
      IF(X(J,K+16).EQ.3.0)FLO(J,K)=3.5
      IF(X(J,K+16).EQ.3.5)FLO(J,K)=3.0
    7 IF(FLO(J,K).LE.2.0) GO TO 10
      IF(FLO(J,K).LT.4.0.AND.FLO(J,K).GE.3.0)GO TO 20
      IF(FLO(J,K).GE.4.0) GO TO 30
   10 IF(FLO(J,K).EQ.1.0) X(J,K+94)=VA
      IF(FLO(J,K).EQ.2.0) X(J,K+102)=VA
      GO TO 90
   20 IF(FLO(J,K).EQ.3.5) X(J,K+94)=VA
      IF(FLO(J,K).EQ.3.0) X(J,K+102)=VA
      GO TO 80
   30 IF(FLO(J,K).EQ.4.5) GO TO 40
      IF(FLO(J,K).EQ.4.1) X(J,K+94)=VA
      IF(FLO(J,K).EQ.4.2) X(J,K+102)=VA
      SO=X(J,K+56)/X(J,K+48)
      SW=1.-SO
      AKRW=X(J,K+40)*(2.*SW/ARAT+SW*SW*(1.-2.0/ARAT))
      AKRN=X(J,K+32)*SO*SO
      AAK=AKRW/VW+AKRN/VO
      AKRW=AKRW*X(J,K+74)/AAK/VW
      AKRN=AKRN*X(J,K+74)/AAK/VO
```

SOURCE STATEMENT

```
      X(J,K+94)=ABS(AKRN*AP(J,K)*TIME )
      X(J,K+102)=ABS(AKRW*AP(J,K)*TIME )
      GO TO 80
40    SO=VOF(J,K)/X(J,K+48)
      SW=1.0-SO
      VWET=VW
      VNW=VO
      SWET=SW
      SNW=SO
      IF(GC.LT.0.0)SWET=SO
      IF(GC.LT.0.0)SNW=SW
      IF(GC.LT.0.0) VNW=VW
      IF(GC.LT.0.0) VWET=VO
      RWET=SWET*SWET
      RNW=2.0*VNW*SNW+SNW*SNW*(1.0-2.0*VNW/VWET)
      TOT= RWET/VWET+RNW/VNW
      RAW=RWET/VWET/TOT
      RAN=RNW/VNW/TOT
      IF(SW.EQ.SWET) RW=RAW
      IF(SW.EQ.SWET)  RO=RAN
      IF(SW.EQ.SNW)RW=RAN
      IF(SW.EQ.SNW) RO=RAW
      X(J,K+94)=RO*VA
      X(J,K+102)=RW*VA
80    VOMAX=X(J,K+48)
      VOMIN=0.0
      IF(GC.GT.0.0) VOMAX=0.96*X(J,K+48)
      IF(GC.LT.0.0)VOMIN=0.04*X(J,K+48)
      IF(VOMAX.LT.VOF(J,K))VOMAX=X(J,K+48)
      IF(VOMIN.GT.VOF(J,K))VOMIN=0.0
      VWMAX=X(J,K+48)-VOMIN
      VWMIN=X(J,K+48)-VOMAX
      IF(FLO(J,K).GT.4.0)GO TO 83
      IF(FLO(J,K).EQ.4.2.OR.FLO(J,K).EQ.3.0) GO TO 85
      V=VA+VOF(J,K)
      IF(V.GT.VOMAX) GO TO 82
      VOF(J,K)=VOF(J,K)+VA
      X(J,K+110)=0.0
      X(J,K+118)=VA
      IF(GC.GT.0.0)FLO(J,K)=4.5
      GO TO 100
82    CONTINUE
      X(J,K+110)=V-VOMAX
      X(J,K+118)=VOMAX-VOF(J,K)
      VOF(J,K)=VOMAX
      FLO(J,K)=1.0
      GO TO 100
85    V=VA+X(J,K+48)-VOF(J,K)
      IF(V.GT.VWMAX) GO TO 86
      VOF(J,K)=VOF(J,K)-VA
      X(J,K+110)=VA
      X(J,K+118)=0.0
      GO TO 100
86    CONTINUE
      X(J,K+110)=VOF(J,K)-VOMIN
```

```
N      SOURCE STATEMENT

           X(J,K+118)=VA-X(J,K+110)
           VOF(J,K)=VOMIN
           FLO(J,K)=2.0
           GO TO 100
        35 V=VOF(J,K)-VOMIN
           IF(V.LT.X(J,K+94))GO TO 84
           VOF(J,K)=VOF(J,K)-X(J,K+94)
           GO TO 90
        84 X(J,K+94)=VOF(J,K)-VOMIN
           X(J,K+102)=VA-X(J,K+94)
           VOF(J,K)=VOMIN
           FLO(J,K)=2.0
        90 X(J,K+110)=X(J,K+94)
           X(J,K+118)=X(J,K+102)
       100 IF(CASE.EQ.2.0) GO TO 150
           X(J,93)=X(J,93)+X(J,K+94)
           X(J,94)=X(J,94)+X(J,K+102)
           GO TO 200
       150 CONTINUE
           X(J,K+94)=X(J,K+110)
           X(J,K+102)=X(J,K+118)
           X(J,83)=X(J,83)+X(J,K+110)
           X(J,84)=X(J,84)+X(J,K+118)
           IF(IJ.LE.JR) X(J,K+24)=2.0
           IF(IJ.GT.IB) X(J,K+24)=2.0
           IF(X(J,K+ 24).EQ.2.0) X(J,K+74)=0.0
           IF(X(J,K+24).EQ.2.0) X(J,K+84)=0.0
           IF(X(J,K+24).EQ.2.0) X(J,K+24)=1.5
           X(J,K+110)=0.0
           X(J,K+118)=0.0
       200 CONTINUE
           RETURN
           END
```

IBMAP ASSEMBLY UB 3 12/ 4/

ESSAGES FOR ABOVE ASSEMBLY

```
$IBFTCSUB 4
      SUBROUTINE COND(KKK)
      COMMON/SYMARG/X(50,16 ),AP(50,8),GC,VO,VW,TIME,VOF(50,8),IJ,IR,JR,
     1XA    ,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID
      COMMON/CHIN/ICAN(50,8),AWDIF(50,8),ADIFO(50,8),BASE
      GO TO (270,79),KKK
C     ENTER CHANGES IN OTHER CONNECTED NODE POINTS
  270 CONTINUE
   11 FORMAT(20X,4I5)
   13 FORMAT(10X,8F13.5)
      N=IR*JR
      JIM=N-JR
      VS=0.0
      IF(BASE.EQ.2.0)VS=1.0
      DO 280 M=1,8
      IF(X(J,M+24).EQ.1.5) GO TO 300
      IF(JIM.LT.IJ) GO TO 273
      IF(X(J,M+64).LE.0.0) GO TO 280
  273 IF(X(J,M+24).GE.2.0) GO TO 280
  300 CONTINUE
      IF(X(J,M).EQ.0.0) GO TO 280
      NX=M+4
      IF(NX.GT.8) NX=M-4
      MMK=IJ+JR-M+4
      IF(M.EQ.1) MMK=IJ-JR+1
      IF(M.EQ.2)MMK=IJ+1
      IF(M.EQ.6)MMK=IJ-1
      IF(M.EQ.7) MMK=IJ-JR-1
      IF(M.EQ.8) MMK=IJ-JR
      IF(MMK.GT.N) GO TO 280
      IF(MMK.LE.0) GO TO 280
      X(MMK,NX+56)=X(J,M+56)
      X(MMK,NX+16)=X(J,M+16)
      IF(X(J,M+16).EQ.4.1) X(MMK,NX+16)=4.1
      IF(X(J,M+16).EQ.4.2) X(MMK,NX+16)=4.2
      IF(X(J,M+16).EQ.3.5) X(MMK,NX+16) =3.0
      IF(X(J,M+16).EQ.3.0) X(MMK,NX+16) =3.5
      IF(X(J,73).EQ.4.0) X(MMK,NX+24)=2.0
      IF(X(J,73).EQ.4.0) X(J,M+24)=2.0
      IF(X(MMK,73).EQ.4.0) GO TO 275
      IF(X(J,M+24).EQ.1.5) X(MMK,NX+24)=2.0
      IF(X(J,M+24).EQ.1.5) X(J,M+24) =2.0
      IF(X(MMK,NX+24).EQ.2.0) X(MMK,NX+74)=0.0
      IF(X(MMK,NX+24).EQ.2.0) X(MMK,NX+84)=0.0
      IF(X(MMK,NX+24).EQ.2.0) X(J,M+74)=0.0
      IF(X(MMK,NX+24).EQ.2.0) X(J,M+84)=0.0
      IF(X(MMK,NX+24).EQ.2.0) GO TO 275
  274 IF(CAT.NE.1.0) GO TO 275
      IF(X(J,M+24).EQ.1.5)X(MMK,NX+24)=2.0
      IF(X(J,M+24).EQ.1.5)X(J,M+24)=2.0
      IF(VS.NE.0.0) GO TO 275
      IF(M.EQ.1.OR.M.GE.7) GO TO 272
      X(MMK,83)=X(MMK,83)+X(J,M+110)
      X(MMK,84)=X(MMK,84)+X(J,M+118)
      GO TO 275
```

```
  272 CONTINUE
      IF(X(J,M+16).EQ.3.0.OR.X(J,M+16).EQ.3.5) GO TO 275
      IF(X(J,M+110).NE.X(MMK,NX+94)) ADIFO(J,M)=X(J,M+110)-X(MMK,NX+94)
      IF(X(J,M+118).NE.X(MMK,NX+102)) AWDIF(J,M)=X(J,M+118)-X(MMK,NX+
     1102)
      IF(ADIFO(J,M).NE.0.0.AND.AWDIF(J,M).NE.0.0) BASE=1.0
      X(MMK,NX+94)=X(J,M+110)
      X(MMK,NX+102)=X(J,M+118)
      IF(BASE.EQ.1.0) ICAN(J,M)=MMK
      IF(BASE.EQ.1.0)PRINT 13,X(J,M+74),X(J,M+64),X(J,M+16),X(MMK,NX+74),
     1X(MMK,NX+64),X(MMK,NX+16)
      IF(BASE.EQ.0.0.AND.X(J,M+24).GE.2.0)PRINT 11,IJ,MMK,ICAN(J,M)
      IF(BASE.EQ.0.0.AND.X(J,M+24).GE.2.0) PRINT 13,X(J,M+110),X(J,M+11
     1),X(J,M+94),X(J,M+102)
  275 CONTINUE
  280 CONTINUE
      GO TO 500
C     FILL PROPER CONDUCTIVITIES
   79 DO 78 K=1,8
      BASE=0.0
      IF(X(J,K).EQ.0.0) GO TO 78
      IF(CAT.EQ.3.0)X(J,K+24)=1.0
      IF(X(J,73).EQ.4.0) X(J,73)=3.0
      SO=X(J,K+56)/X(J,K+48)
      SW=1.0-SO
      IF(X(J,K+16).EQ.1.0) X(J,K+74)=X(J,K+32)
      IF(X(J,K+16).EQ.2.0) X(J,K+74)=X(J,K+40)
      IF(X(J,K+16).EQ.1.0.OR.X(J,K+16).EQ.2.0) GO TO 830
      IF(X(J,K+16).NE.4.5) GO TO 821
      VL=VO
      IF(VW.GT.VL) VL=VW
      X(J,K+74)=X(J,K+32)*VO/(VO*SO+VW*SW+6.0*VL*X(J,K))
      GO TO 830
  821 IF(X(J,K+16).EQ.3.0.OR.X(J,K+16).EQ.3.5) GO TO 822
      GO TO 823
  822 X(J,K+74)=X(J,K+32) *VO/(VO*SO+VW*SW)
      GO TO 830
  823 ARAT=VO/VW
      IF(GC.GE.0.0) GO TO 824
      IF(GC.LT.0.0) GO TO 825
  824 AKRW=SW*SW*X(J,K+40)
      AKRN=X(J,K+32)*(2.0*SO*ARAT+SO*SO*(1.0-2.0*ARAT))
      TOT=AKRW/VW+AKRN/VO
      X(J,K+74)=X(J,K+32)*VO*TOT
      GO TO 830
  825 AKRW=X(J,K+40)*(2.0*SW/ARAT+SO*SO*(1.0-2.0/ARAT))
      AKRN=X(J,K+32)*SO*SO
      TOT=AKRW/VW+AKRN/VO
      X(J,K+74)=TOT*VO*X(J,K+32)
  830 CONTINUE
      X(J,K+74)=ABS(X(J,K+74))
      X(J,K+110)=0.0
      X(J,K+118)=0.0
      X(J,K+84)=0.0
      X(J,83)=0.0
```

```
SN        SOURCE STATEMENT

21        X(J,84)=0.0                                          BPP07640
22        IK=J/JR+1                                            BPP07650
23        JK=J-JR*(IK-1)                                       BPP07660
24        IF(JK.LE.0)IK=IK-1                                   BPP07670
27        IF(JK.LE.0)JK=JR                                     BPP07680
2         IF(IK.EQ.1)GO TO 140                                 BPP07690
5         IF(IK.EQ.2.AND.K.EQ.1)GO TO 140                      BPP07700
[illegible] IF(IK.EQ.2.AND.K.GE.7)GO TO 140                    BPP07710
.3        R=GC*((1.0/XA)-(1.0/X(J,K)))                         BPP07720
.4        R=-R                                                 BPP07730
.5        GO TO 150                                            BPP07740
.6    140 R=GC/X(J,K)                                          BPP07750
.7    150 CONTINUE                                             BPP07760
.8        IF(X(J,K+16).EQ.3.0) X(J,K+84)= R                    BPP07770
3         IF(X(J,K+16).EQ.3.5) X(J,K+84)=-R                    BPP07780
6      78 CONTINUE                                             BPP07790
0     500 RETURN                                               BPP07800
1         END                                                  BPP07810
```


ESSAGES FOR ABOVE ASSEMBLY

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ISN       SOURCE STATEMENT

 $IBFTCSUB 5                                                            BPP07820
          SUBROUTINE CHANGE                                             BPP07830
          COMMON/SYMARG/X(50,160),AP(50,8),GC,VD,VW,TIME,VOF(50,8),IJ,IR,JR,BPP07840
         1XA    ,EP(10,10),HYST,CAT,GAMMA,J,FLD(50,8),GRID             BPP07850
          COMMON/CHAN/DIFO,WDIF                                         BPP07860
          COMMON/SOLB/CAP(10,10),I,ICHANG,ARAT,TRAP                     BPP07861
          COMMON/SOLC/ADD,CP,JIM,ICP                                    BPP07862
          DIMENSION B(9),C(8)                                           BPP07870
          REAL KA                                                       BPP07880
      69  FORMAT(2 X,5HDIFO=,E13.5,5X,5HWDIF=,E13.5)                   BPP07890
          IF(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT68 ,DIFO,WDIF        BPP07891
          IF(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT680,(X(J,K),K=17,24) BPP07892
          IF(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT680,(X(J,K),K=75,82) BPP07893
          IF(ICP.EQ.2.AND.I.GE.17.AND.J.EQ.22)PRINT680,(X(J,K+94),K=1,32)  BPP07894
     680  FORMAT(1X,8E15.7)                                             BPP07895
          DO 550 K=1,8                                                  BPP07900
 C        SELECT TUBES FOR FLOW CHANGES SO THAT MATERIAL BALANCE FOR EACH PHBPP07910
 C        IS SATISFIED IN EACH NODE OF THE MODEL                        BPP07920
          C(K)=0.0                                                      BPP07930
     550  CONTINUE                                                      BPP07940
 C        ETTING FLUID IMBIBITION                                       BPP07950
          BASE=0.0                                                      BPP07960
          KA=0.0                                                        BPP07970
          CAT=0.0                                                       BPP07980
          ACE=0.0                                                       BPP07981
          IF(GC.GE.0.0.AND.WDIF.GT.0.0) KA=1.0                          BPP07990
          IF(GC.LT.0.0.AND.DIFO.GT.0.0) KA=2.0                          BPP08000
          IF(KA.EQ.0.0)KA=4.5                                           BPP08010
          IF(KA.EQ.4.5) CAT=0.3                                         BPP08020
     554  B(1)=0.0                                                      BPP08030
          DO 555 K=1,8                                                  BPP08040
          V=0.0                                                         BPP08050
          IF(X(J,K+24).GE.2.0)GO TO 555                                 BPP08060
          IF(C(K).NE.0.0) GO TO 555                                     BPP08070
          IF(FLD(J,K).NE.KA) GO TO 555                                  BPP08080
          IF(AP(J,K).LE.0.0) GO TO 555                                  BPP08081
          V=AP(J,K)*X(J,K+74)                                           BPP08090
          V=ABS(V)                                                      BPP08100
     555  B(K+1)=B(K)+V                                                 BPP08110
     556  CONTINUE                                                      BPP08120
          IF(B(9).EQ.0.0) GO TO 559                                     BPP08130
          RN=RNDY1(0.)                                                  BPP08140
          DO 557 K=2,9                                                  BPP08150
          IF(RN.LE.B(K)/B(9)) GO TO 558                                 BPP08160
     557  CONTINUE                                                      BPP08170
     558  K=K-1                                                         BPP08180
          C(K)=1.0                                                      BPP08190
          GO TO 570                                                     BPP08200
 C        PENDULAR FLOW CHANGE                                          BPP08210
     559  IF(CAT.GE.0.3) GO TO 560                                      BPP08220
          KA=4.5                                                        BPP08230
          CAT=0.3                                                       BPP08240
          GO TO 554                                                     BPP08250
     560  IF(CAT.EQ.0.3) GO TO 561                                      BPP08260
          IF(CAT.EQ.0.4) GO TO 562                                      BPP08270
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      SOURCE STATEMENT

      IF(CAT.EQ.0.5) GO TO 563
      IF(CAT.EQ.0.6) GO TO 564
      IF(CAT.EQ.0.8)GO TO 565
      GO TO 620
  561 CONTINUE
C     SLUG FLOW CHANGE
      IF(WDIF.GT.0.0)KA=4.2
      IF(DIFO.GT.0.0) KA=4.2
      CAT=0.4
      GO TO 554
  555 IF(WDIF.GT.0.0)KA=4.1
      IF(DIFO.GT.0.0)KA=4.1
      CAT=0.8
      GO TO 554
  562 CONTINUE
C     DISPLACEMENT FLOW CHANGE
      IF(DIFO.GT.0.0) KA=3.0
      IF(WDIF.GT.0.0) KA=3.5
      CAT=0.5
      GO TO 554
  563 CONTINUE
C     NON WETTING FLUID IMBIBITION
      KA=0.0
      IF(DIFO.GT.0.0)KA=2.0
      IF(WDIF.GT.0.0)KA=1.0
      CAT=0.6
      GO TO 554
  564 CONTINUE
      IF(WDIF.GT.0.0)KA=3.0
      IF(DIFO.GT.0.0)KA=3.5
      CAT=0.7
      IF(KA.EQ.0.0)GO TO 620
      GO TO 554
  570 V=AP(J,K)*X(J,K+74)*TIME
      FLO(J,K)=KA
      IF(KA.EQ.3.0)FLO(J,K)=3.0
      IF(KA.EQ.3.5)FLO(J,K)=3.5
      IF(KA.EQ.4.1)FLO(J,K)=4.1
      IF(KA.EQ.4.2)FLO(J,K)=4.2
      IF(KA.EQ.1.0) FLO(J,K)=3.0
      IF(KA.EQ.2.0) FLO(J,K)=3.5
      IF(CAT.EQ.0.5)FLO(J,K)=4.5
      VOMAX=X(J,K+48)
      VOMIN=0.0
      IF(GC.LT.0.0) VOMIN=0.04*VOMAX
      IF(GC.GE.0.0) VOMAX=0.96*VOMAX
      IF(X(J,K+56).GT.VOMAX) VOMAX=X(J,K+48)
      IF(X(J,K+56).LT.VOMIN) VOMIN=0.0
      VWMAX=X(J,K+48)-VOMIN
      VWMIN=X(J,K+48)-VOMAX
      VOLO=VOMAX-X(J,K+56)
      VOLW=X(J,K+56)-VOMIN
      CASE=0.0
      IF(DIFO.GT.0.0) V=X(J,K+102)
      IF(WDIF.GT.0.0) V=X(J,K+94)
```

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      SOURCE STATEMENT

      IF(WDIF.GT.0.0) GO TO 601
      IF(DIFO.GT.0.0) GO TO 603
C     WATER EXCESS
  601 IF(V.GT.WDIF) GO TO 602
      WDIF=WDIF-V
      X(J,K+94)=0.0
      X(J,K+102)=X(J,K+102)+V
      IF(V.LT.VOLW) GO TO 11
      FLO(J,K)=2.0
      VOF(J,K)=VOMIN
      GO TO 554
   11 VOF(J,K)=X(J,K+56)-V
      GO TO 12
  602 VOF(J,K)=VOMIN
      IF(VOLW.GT.WDIF) VOF(J,K)=X(J,K+56)-WDIF
      IF(VOLW.LT.WDIF) FLO(J,K)=2.0
      IF(GC.LT.0.0.AND.FLO(J,K).EQ.2.0) FLO(J,K)=4.5
      X(J,K+94)=X(J,K+94)-WDIF
      X(J,K+102)=X(J,K+102)+WDIF
      WDIF=0.0
   12 CONTINUE
      SO=VOF(J,K)/X(J,K+48)
      IF(FLO(J,K).EQ. 4.5.AND.GC.GT.0.0) CASE=0.5
      IF(CASE.EQ.0.5.AND.SO.LT.0.80)FLO(J,K)=4.1
      IF(FLO(J,K).EQ.4.2.OR.FLO(J,K).EQ.4.1) BASE=1.0
      IF(BASE.EQ.1.0.AND.GC.GE.0.0) CASE=1.0
      IF(BASE.EQ.1.0.AND.GC.LT.0.0) CASE=2.0
      IF(CASE.EQ.1.0.AND.SO.GE.0.8) FLO(J,K)=4.5
      IF(CASE.EQ.2.0.AND.SO.LE.0.2) FLO(J,K)=4.5
      CASE=0.0
      BASE=0.0
      IF(WDIF.NE.0.0)GO TO 554
      GO TO 590
C     OIL EXCESS
  603 IF(V.GT.DIFO) GO TO 604
      DIFO=DIFO-V
      X(J,K+94)=X(J,K+94)+V
      X(J,K+102)=0.0
      IF(V.LT.VOLO) GO TO 13
      VOF(J,K)=VOMAX
      FLO(J,K)=1.0
      IF(GC.GT.0.0) FLO(J,K)=4.5
      GO TO 554
   13 VOF(J,K)=X(J,K+56)+V
      GO TO 14
  604 VOF(J,K)=VOMAX
      IF(VOLO.GT.DIFO) VOF(J,K)=X(J,K+56)+DIFO
      IF(VOLO.LT.DIFO) FLO(J,K)=1.0
      IF(GC.GE.0.0.AND.FLO(J,K).EQ.1.0) FLO(J,K)=4.5
      X(J,K+102)=X(J,K+102)-DIFO
      X(J,K+94)=X(J,K+94)+DIFO
      DIFO=0.0
   14 CONTINUE
      SO=VOF(J,K)/X(J,K+48)
      IF(FLO(J,K).EQ.4.5.AND.GC.LE.0.0)CASE=0.5
```

FORTRAN SOURCE LIST UB 5 12/04

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      SOURCE STATEMENT

      IF(CASE.EQ.0.5.AND.SO.GT.0.2)FLO(J,K)=4.2                         BPP09270
      IF(FLO(J,K).EQ.4.2.OR.FLO(J,K).EQ.4.1)BASE=1.0                    BPP09280
      IF(BASE.EQ.1.0.AND.GC.LT.0.0) CASE=1.0                            BPP09290
      IF(BASE.EQ.1.0.AND.GC.GE.0.0)CASE=2.0                             BPP09300
      IF(CASE.EQ.1.0.AND.SO.LE.0.2) FLO(J,K)=4.5                        BPP09310
      IF(CASE.EQ.2.0.AND.SO.GE.0.8) FLO(J,K)=4.5                        BPP09320
      BASE=0.0                                                          BPP09330
      CASE=0.                                                           BPP09340
      IF(DIFO.NE.0.0) GO TO 554                                         BPP09350
  590 CONTINUE                                                          BPP09360
  620 IF(DIFO.LE.0.10E-10)DIFO=0.0                                      BPP09370
      IF(WDIF.LE.0.10E-10)WDIF=0.0                                      BPP09380
      IF(DIFO.EQ.0.0.AND.WDIF.EQ.0.0)GO TO 630                          BPP09381
      ACE=ACE+1.0                                                       BPP09382
      DO 35 K=1,8                                                       BPP09383
   35 C(K)=0.0                                                          BPP09384
      CAT=0.3                                                           BPP09385
      KA=4.5                                                            BPP09386
      IF(ACE.EQ.1.0)GO TO 554                                           BPP09387
  630 IF(WDIF.NE.0.0.OR.DIFO.NE.0.0)PRINT690,DIFO,WDIF                  BPP09390
      RETURN                                                            BPP09400
      END                                                               BPP09410
```

FORTRAN PROGRAM UB 5 12/04

FUNCTION SUBPROGRAM REFERENCES

IBMAP ASSEMBLY UB 5 12/04

ESSAGES FOR ABOVE ASSEMBLY

SOURCE STATEMENT

```
$IBFTC SUB 6
      SUBROUTINE PDIF
      COMMON/SYMARG/X(50,160),AP(50,8),GC,VO,VW,TIME,VOF(50,8),IJ,IR,JR,
     1XA    ,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID
C      FILL PRESS DIFFERENTIALS FOR ALL TUBES AT EACH NODE POINT
      J=IJ
      IK=IJ/JR+1
      JK= IJ-JR*(IK-1)
      IF(JK.LE.0)IK=IK-1
      IF(JK.LE.0)JK=JR
   35 FORMAT(1X,2I5)
      X(J,74)=EP(IK,JK)
      IF(IK.EQ.1)GO TO 87
      IF(JK.EQ.1)GO TO 92
      IF(IK.EQ.IR) GO TO 96
      IF(JK.EQ.JR) GO TO 100
      X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)
      X(J,66)=EP(IK,JK)-EP(IK,JK+1)
      X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)
      X(J,68)=EP(IK,JK)-EP(IK+1,JK)
      X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)
      X(J,70)=EP(IK,JK)-EP(IK,JK-1)
      X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)
      X(J,72)=EP(IK,JK)-EP(IK-1,JK)
      GO TO 102
   87 IF(JK.EQ.1) GO TO 88
      IF(JK.EQ.JR) GO TO 90
      X(J,65)=0.0
      X(J,66)=0.0
      X(J,70)=0.0
      X(J,71)=0.0
      X(J, 72)=0.0
      X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)
      X(J,68)=EP(IK,JK)-EP(IK+1,JK)
      X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)
      GO TO 102
   88 X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)
      DO 89 K=1,8
      IF(K.EQ.3) GO TO 89
      X(J,K+64)=0.
   89 CONTINUE
      GO TO 102
   90 X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)
      DO 91 K=1,8
      IF(K.EQ.5) GO TO 91
      X(J,K+64)=0.
   91 CONTINUE
      GO TO 102
   92 IF(IK.EQ.IR) GO TO 94
      X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)
      X(J,66)=EP(IK,JK)-EP(IK,JK+1)
      X(J,67)=EP(IK,JK)-EP(IK+1,JK+1)
      DO 93 K=4,8
      X(J,K+64)=0.0
   93 CONTINUE
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SN        SOURCE STATEMENT

          GO TO 102
       94 X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)
          DO 95 K=2,8
          X(J,K+64)=0.0
       95 CONTINUE
          GO TO 102
       96 IF(JK.EQ.JR) GO TO 98
          X(J,65)=EP(IK,JK)-EP(IK-1,JK+1)
          X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)
          X(J,72)=EP(IK,JK)-EP(IK-1,JK)
          DO 97 K=2,6
          X(J,K+64)=0.0
       97 CONTINUE
          GO TO 102
       98 X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)
          DO 99 K=1,8
          IF(K.EQ.7)GO TO 99
          X(J,K+64)= .
       99 CONTINUE
          GO TO 102
      100 X(J,69)=EP(IK,JK)-EP(IK+1,JK-1)
          X(J,70)=EP(IK,JK)-EP(IK,JK-1)
          X(J,71)=EP(IK,JK)-EP(IK-1,JK-1)
          X(J,72)=0.0
          DO 101 K=1,4
          X(J,K+64)=0.0
      101 CONTINUE
      102 CONTINUE
 C        FILL POSITIVE DIFFERENTIAL PR. AND CAP. PR.
          DO 104 K=1,8
          VOF(J,K)=0.0
          AP(J,K)=0.0
          IF(X(J,K).EQ.0.0) GO TO 104
          X(J,K+64)=X(J,K+64)+X(J, K+84)
          IF(X(J,K+64).GT.0.0)AP(J,K)=X(J,K+64)
      104 CONTINUE
          RETURN
          END
```


ESSAGES FOR ABOVE ASSEMBLY

SOURCE STATEMENT

```
$IBFTCSUB 7
      SUBROUTINE SIMU
C     PROGRAM SIMU
      COMMON/SYMARG/X(50,160),AP(50,8),GC,VO,VW,TIME,VOF(50,8),IJ,IR,JR,
     1XA     ,EP(10,10),HYST,CAT,GAMMA,J,FLO(50,8),GRID
      COMMON/SOLC/ADD,CP,JIM,ICP
      COMMON/SIM/COM(15),RAD(15),KL,LK
      DIMENSION E(50,8)
      FACT=6[illegible]947.0*1.35/1.732
      DO 50 J=1,JR
      DO 6  I=1,IR
      ISK=(I-1)*JR+J
      DO 20 M=1,8
      X(ISK,M+8)=1.0
      X(ISK,M+16)=1.0
      X(ISK,M+24)=1.0
      X(ISK,M+32)=1.0
      X(ISK,M+40)=1.0
      X(ISK,M+48)=1.0
      X(ISK,M+56)=1.0
      X(ISK,M+64)=1.0
   20 CONTINUE
      X(ISK,73)=1.
      X(ISK,74)=1.0
      IF(J.EQ.JR) GO TO 120
      DO 70 K=1,4
      RN=RNDY1(Y)
      DO 75 M=1,LK
      IF(RN.LE.COM(M)) GO TO 100
   75 CONTINUE
  100 X(ISK,K)=RAD(M)
   70 CONTINUE
      GO TO 130
  120 DO 160 K=1,4
      X(ISK,8)=0.0
  160 CONTINUE
      X(ISK,1)=0.0
  130 IF(J.NE.1) GO TO 150
      DO 165 K=4,8
      X(ISK,K)=0.0
  165 CONTINUE
  150 IF(I.NE.1) GO TO 155
      X(ISK,1)=0.0
      X(ISK,2)=0.0
      X(ISK,6)=0.0
      X(ISK,7)=0.0
      X(ISK,8)=0.0
  155 IF(I.NE.IR) GO TO 180
      DO 195 K=2,6
      X(ISK,K)=0.0
  195 CONTINUE
C     FILL ALL TUBE RADII
  180 IF(J.EQ.1)  GO TO 190
      DO 135 N=1,3
      IF(I.EQ.1.AND.N.NE.1) GO TO 135
```

SOURCE STATEMENT

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      IF(I.EQ.IR.AND.N.NE.3) GO TO 135
      IP=I-N+2
      IS=(IP-1)*JR+J-1
      X(ISK,N+4)=X(IS,N)
  135 CONTINUE
      IF(I.EQ.1) GO TO 190
      IS=(I-2)*JR+J
      X(ISK,3)=X(IS,4)
  190 CONTINUE
C     FILL LENGTH IN 9-16
      DO 230 K=9,16
      X(ISK,9)=1.4142
      IF(X(ISK,K-1).EQ.1.0) X(ISK,K)=1.4142
  230 CONTINUE
C     FILL OIL AND WATER CONDUCTIVITIES IN 33-40AND41-48RESPECTIVELY
      DO 300 K=1,8
      X(ISK,K+8)=X(ISK,K+8)*GRID
      B(ISK,K)=(FACT*X(ISK,K)**4)/X(ISK,K+8)
      X(ISK,K+32)=B(ISK,K)/VO
      X(ISK,K+40)=B(ISK,K)/VW
C     COMPUTE VOLUMES OF TUBES
      X(ISK,K+48)=3.0*1.732*X(ISK,K+8)*X(ISK,K)**2.0
C     FILL FLOW OF OIL IN ALL TUBES 75-64
      X(ISK,K+56)=X(ISK,K+48)
      X(ISK,K+74)=X(ISK,K+32)
      X(ISK,K+84)=0.0
      X(ISK,K+94)=0.0
      X(ISK,K+102)=0.0
      X(ISK,K+110)=0.0
      X(ISK,K+118)=0.0
      X(ISK,K+128)=0.0
      X(ISK,K+136)=0.0
      X(ISK,K+144)=0.0
      X(ISK,K+152)=0.0
      IF(X(ISK,K).EQ.0.0) X(ISK,K+24)=2.0
  300 CONTINUE
      X(ISK,8_)=0.0
      X(ISK,84)=0.0
      X(ISK,9_)=0.0
      X(ISK,94)=0.0
      X(ISK,127)=0.0
      X(ISK,128)=0.0
C     ASSIGN VALUES TO DEL PR IN 65-72
      IAN=IR-1
      AN=IAN
      Z=CP/AN
      DO 301 K=3,5
      X(ISK,K+64)=Z
  301 CONTINUE
      X(ISK,71)=-Z
      X(ISK,72)=-Z
      X(ISK,65)=-Z
      X(ISK,66)=0.0
      X(ISK,70)=0.0
C     ASSIGN PRESSURE 74
```

```
                                    FORTRAN SOURCE LIST UB 7                        2/0
SN        SOURCE STATEMENT

5         Y=I                                                                      BPP1 45
6         YS=IR                                                                    BPP11460
7         X(ISK,74)=CP*(YS-Y)/(YS-1.0)                                             BPP11470
0         IJ=(I-1)*JR+J                                                            BPP1 4
1       1 FORMAT(5X,8E15.7)                                                        BPP1 49
2      50 CONTINUE                                                                 BPP1 50
4      50 CONTINUE                                                                 BPP1 51
6         RETURN                                                                   BPP1152
7         END                                                                      BPP1153
                                    FORTRAN  PROGRAM  UB 7                          12/04
 FUNCTION SUBPROGRAM REFERENCES


                                    IBMAP ASSEMBLY UB 7                             12/04

ESSAGES FOR ABOVE ASSEMBLY
                                    IBLDR -- JOB                                    12/04/

    ***  OBJECT PROGRAM IS BEING ENTERED INTO STORAGE AT  08 HRS.  32 MTS.  02 SECS
```